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PREFACE

This issue, Number 1 of Volume 49, contains the papers presented at the Pacific Coast Convention held at Santa Monica, California, September 3-6, 1929, and at the Great Lakes District Meeting, Chicago, Illinois, December 2-4, 1929.

Three miscellaneous contributions are also included: *Power Transients in A-C. Motors*, by L. E. A. Kelso and G. F. Tracy, *General Circle Diagram of Electrical Machinery*, by F. E. Terman, T. L. Lenzen, C. L. Freedman, and K. A. Rogers, and *Effect of Electric Shock*, by W. B. Kouwenhoven and Orthello Langworthy.

For the reader's convenience an index of the authors and discussors included in this issue is appended. The complete annual index will appear in the October Quarterly.

Radio Interference from Line Insulators

BY ELLIS VAN ATTA[1] and E. L. WHITE[2]

Non-member — Associate, A. I. E. E.

Synopsis.—This paper presents a discussion of the causes of radio interference from insulators on high-voltage equipment. The present methods of eliminating this kind of disturbance are explained, and the question of future design is discussed.

INTRODUCTION

RADIO broadcasting has brought with it the problem of radio interference. The radio listener is, of course, the one most affected by interference; but the broadcasting companies, the manufacturers of electrical apparatus, and the producers of electrical energy are likewise concerned since the solution of the problem devolves upon them. During the past few years each of these interests has done much to eliminate unnecessary interference; and every kind of equipment used in the supply and consumption of electrical energy has been tried and tested for interfering qualities.

Their experience has shown that radio interference may be classified under five headings, with respect to its origin. These sources are as follows:

1. Consumers' equipment.
2. Low-voltage supply circuits and apparatus (110-550 volts).
3. Intermediate-voltage circuits and equipment (1100-7500 volts).
4. High-voltage equipment (11,000-220,000 volts).
5. Atmospheric disturbances.

Ways have been devised for eliminating practically all radio interference which originates on any of the first three classes of equipment. The last item is obviously beyond human control. The fourth classification includes numerous items of equipment which can be made free from radio interference, and a few other items for which no remedy has been devised as yet. The scope of this paper is limited to the latter group, particularly line insulators of the pin and suspension types.

GENERAL

The principles underlying radio interference are similar to those of spark telegraphy and carrier current telephony. In brief, a spark occurring on electrical equipment of any kind sets up a wave train which produces damped oscillations at a multitude of frequencies. The predominating frequencies are the resonant frequencies of the associated lines and equipment, and their harmonics, including those in the radio broadcasting band.

Since the electrical constants which determine the above frequencies are distributed, and several kinds of equipment may be concerned, the resonant peaks are usually broad and overlapping. Consequently a broadcast receiver which has radio interference is usually affected over the entire broadcasting range, with occasional points of greater disturbance.

The extreme sensitiveness of modern receivers, and the use of a-c. supply, make them very susceptible to radio interference. The comparatively small amounts of energy involved in the electrical discharges described later are therefore sufficient to produce a great amount of disturbance in broadcast receivers, particularly when the discharges occur along high-voltage lines.

The distinction between corona and brush discharge should be kept in mind when radio interference from line insulators is considered. Corona discharge usually occurs at lower voltages than brush discharge, and appears as a bluish glow when viewed in a dark room. Brush discharge occurs after corona discharge, and takes the form of fine white streamers. This condition is usually considered as another form of corona discharge, but will be classed separately in this case because of the different interfering characteristics of the two discharges. In a broadcast receiver, corona discharge produces a soft, hissing sound which is not ordinarily objectionable. Brush discharge, however, produces a crackling, frying noise which is very annoying.

PIN-TYPE INSULATORS

Corona and brush discharges may occur on high-voltage lines in any or all of the following ways:

1. Between metallic surfaces.
2. Between insulating surfaces.
3. Between metallic surfaces and insulating surfaces.

To entirely free a line of radio interference, all discharges must be stopped. In order to accomplish this purpose, all hardware must be tight; adjacent pieces of hardware must either have sufficient separation to prevent discharges, or must be bonded together; conductors and tie-wires must make perfect electrical contact with the tops of the insulators; and the pins must make perfect electrical contact with the entire surface of the thread in the pin holes. On lines using pin-type insulators these requirements can be met with the exception of the last two. Conductors, tie-wires, and pins do not make good electrical contact with the surfaces of the insulators, and every insulator is therefore a potential source of radio interference.

For the purpose of this discussion, a pin-type insulator

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will be considered as the dielectric of a condenser, with the conductor and tie wire acting as one plate and the pin acting as the other. When potential is applied to the plates, a charging current, the magnitude of which is determined by the reactance of the condenser and the applied voltage, will flow into the condenser. Since the reactance of a condenser is a function of its electrostatic capacity and the frequency of the applied voltage, it follows that the charging current is affected by the three factors, voltage, frequency, and capacity.

Consider a 66-kv. pin-type insulator, whose electrostatic capacity is approximately 10 $\mu\mu$f. A charging current of 0.14 milliamperes will flow into it when used on a line operated at a voltage of 38.1 kv. to ground and a frequency of 60 cycles per second. If the conductor, tie-wire, and pin all made perfect electrical contact with the insulating surfaces, this charging current could easily flow into the insulator. Unfortunately, resistance is offered to the flow of charging current by insufficient contact between the wires, pins, and insulating surfaces. Due to the fact that the dielectric strength of air is lower than that of the insulator material, the potential differences at these points of poor contact are sufficient to ionize the adjacent air, with resultant corona and brush discharges.

The problem of radio interference from pin-type insulators is thus reduced to the matter of overcoming resistance to the flow of charging current into the insulator.

Since the magnitude of the charging current into the insulator is determined by the voltage and the frequency applied, and by the electrostatic capacity of the insulator, a reduction in any of these factors will decrease the charging current. In practise, the voltage and frequency are fixed, but the capacity can be reduced by overinsulating the lines. This method has been tried with only partial success, particularly on lines operated at 55 and 66 kv. If larger pin-type insulators are used, the problem of insufficient contact between wire, pin, and insulator is still present.

The best solution of the problem appears to be some method of insuring good contact between the conductors, tie-wires, and insulating surfaces. On existing pin-type insulators, this result can probably be secured by treating the insulator heads and pin-holes in some manner which will eliminate the poor contact between the wires, pins, and insulators.

Metallic paints have been tried, without success, because such paints form a coating of metal particles suspended in varnish and do not offer a good conducting surface. Metal disks, attached to the conductors above the insulators, have proved partially successful, due to the reduction in current density where the conductors and tie-wires contact the insulators. Tests have shown that the same result may be accomplished by looping the tie-wire to form a ring several inches in diameter over the head of the insulator. Tests have also shown that discharges to the heads of insulators are materially reduced by the addition of several extra turns of tie-wire in the insulator grooves. Metal gauze, placed in the tie-wire groove, has proved effective in some cases, and seems to be the best solution of the problem at the present time. Experiments are still being conducted, however, and it is hoped that a compound can be found which will fill in the air spaces between wires and insulators, will be unaffected by weather conditions, and will not be expensive to apply.

The problem of new pin-type insulators is being attacked in several ways. Some manufacturers employ a metal cap cemented on the head of a standard insulator. Another one uses solder-impregnated gauze in the tie-wire groove. Other insulators have layers of metal applied to the heads and the wire grooves. These metals are of various kinds and varying thicknesses. Most of them are too thin to be practical but all have a good contact surface. Still another insulator is treated in the wire grooves and the pin-hole with a special glaze. This last insulator proved to be the best of all when subjected to rated voltage in a comparative test.

Obviously, the use of metal-coated heads and metal caps on pin-type insulators will result in an increase in the electrostatic capacity of such insulators. The charging current will be increased and consequently the current density at the surface of the pin-hole will be increased. Tests have shown that this point is a very important one. It is therefore imperative that the pin-hole be treated in some manner to insure good contact between the pin and the insulator. Metal threads, cemented into the insulator, are being used in most cases, while one insulator is treated with a special glaze, as mentioned before.

At the beginning of this discussion it was stated that corona and brush discharges may occur between insulating surfaces such as the petticoats of pin-type insulators. The presence of such discharges is an indication of faulty design or too high an applied voltage. The remedy is obvious in either case.

Suspension Insulators

Suspension insulators can be classified under three general types, cap-and-pin, link, and spider. The cap-and-pin type, as the name implies, consists of a porcelain disk with a cap cemented to one side, and a pin to the other. Two kinds of hardware are used for attaching adjacent units, the clevis type and the ball-and-socket type. The link type of insulator consists of porcelain disks connected together by loops of metal, so that the porcelain is in compression. The spider type consists of extra-heavy porcelain disks, with the connecting hardware imbedded in both sides in the form of a spider, and secured by a metal alloy instead of cement.

Until recently, suspension insulators as a group have been considered free from radio interference. The potential impressed upon individual disks of a string, as they are used in practise, is comparatively low. On

55-kv. lines, using three units per phase wire, the maximum duty is about 11,000 volts. For 110-kv. lines using six or seven units per string, the maximum potential per unit is 14,000 volts. On 220-kv. lines, using fourteen units per string, the maximum voltage per unit is 23,000 volts without grading rings or shields, and about 15,000 volts with such devices.

When individual ball-and-socket-type insulators are tested in a dark room corona discharge appears at the cap and at the pin when potentials as low as 18,000 volts are applied. Brush discharge occurs at voltages as low as 26,000. This type of insulator, therefore, should not cause interference under ordinary conditions.

Corona and brush discharges also appear on clevis-type insulators at the above voltages when the cotter key is removed from the clevis bolt. With the cotter key in place, and the pointed ends turned upward, brush discharges occur between the points of the key and the innermost petticoat at potentials as low as 11,000 volts. The cotter keys on clevis-type insulators which have been in service on 110-kv. lines for only short periods, show unmistakable evidence of brush discharge, not only from the pointed ends but from the round ends as well. Cotter keys on the units next to the line are affected most, but the keys on other units also show signs of discharge. Obviously the cotter key is at fault on the clevis-type of insulator, and ways of eliminating this source of interference will be taken up later.

Insulators of the link type are even more liable to cause interference than clevis-type insulators. In the older models, no attempt is made to obtain good contact between the links and the porcelain, and brush discharges take place at potentials as low as 2000 volts per unit. When weights are used to simulate line loading, the brush-discharge potential rises to 4000 volts.

The newer models of link-type insulators employ lead shims, soft copper links, etc., in order to get better contact between the metal and the porcelain. Without loading, radio interference starts at 6000 volts per unit. Under 340-lb. tension, interference does not begin until 14,000 volts are impressed. Since the potential across the line unit of a string of six link-type insulators used on a 110-kv. line is about 20,000 volts, interference will be present under those or similar conditions.

On the spider-type of insulator, corona discharge does not start until potentials of 21,000 volts are applied across individual disks. Brush discharge occurs at 26,000 volts. Both discharge points are higher than the corresponding points for either cap-and-pin or link-type insulators, a fact which is accounted for by the heavy mass of porcelain used in this type of insulator, and the absence of sharp points or rough edges at points of high electrostatic flux density.

Both the spider type and the ball-and-socket type of insulator are designed to have certain values of mechanical strength, flashover voltage, and leakage distance, rather than high values of corona or brush discharge voltage. Fortunately these discharge points are higher than the usual operating voltages, and the insulators are satisfactory from the point of view of radio interference.

Clevis-type insulators are also satisfactory when the cotter key is properly designed. One manufacturer has designed a clevis-type insulator in which the cap is recessed to overlap the cotter key and prevent it from turning. One of the large power companies is replacing the regular cotter key with a circular key, so designed that the ends are concealed inside the clevis bolt when in place. Comparative tests show that clevis-type insulators equipped with circular cotter keys are on a par with ball-and-socket insulators.

The link type of insulator is satisfactory if sufficient loading is applied to keep the porcelain and the links in intimate contact, and the voltage per unit does not exceed 14,000 volts. Much of the discussion pertaining to pin-type insulators is also applicable to link-type insulators. The problems involved are similar and can probably be solved by using similar methods.

Many lines using suspension insulators also use arcing horns to protect the insulator disks during flashover and to prevent burning of the conductor. Grading rings, shields, etc., also accomplish this purpose and change the potential distribution along the insulator string, so that the maximum voltage per unit is very much reduced. Tests show that the arcing horn is the only one of the above devices which ordinarily causes radio interference. Brush discharges take place at the ends of the horns, which produce an interference similar in sound to that of pin-type insulators. These discharges can be eliminated in the present design of arcing horn by adding a small metal ball to the end of the horn. The surface area is thus increased, and sharp points are avoided.

Other Sources of Interference

Pin-type and suspension insulators behave alike when subjected to moisture and dirt. The presence of either of these factors will usually increase the amount of interference, particularly on pin-type insulators. Tests in the laboratory show differences of 50 per cent or more in interference caused by insulators when dirty and the same insulators when cleaned. Moisture has a similar effect as shown by the curves of Fig. 1 where the noise level is three times as high for a line with insulators wet as it is for the same line when dry.

Defective, cracked, and broken insulators of either kind set up a disturbance which often affects radio receiving sets several miles away. Small projections on the surface of the porcelain sometimes create interference, especially when they are located in a heavy electrostatic field. Discharges frequently occur from the ends of tie-wires which are not bent closely enough to the conductor.

The remedy in each case is clear. Defective insulators must be replaced. Dirty insulators can be cleaned.

Wet-weather conditions are sometimes minimized by overinsulation, and tie-wire ends should always be bent back as closely to the conductor as possible. Proper inspection and maintenance are therefore essential to the elimination of radio interference from high-voltage lines.

CURVES

The curves in Fig. 1 are intended to show the effect of attenuation on radio interference which is being propagated along a transmission line, to give an idea of

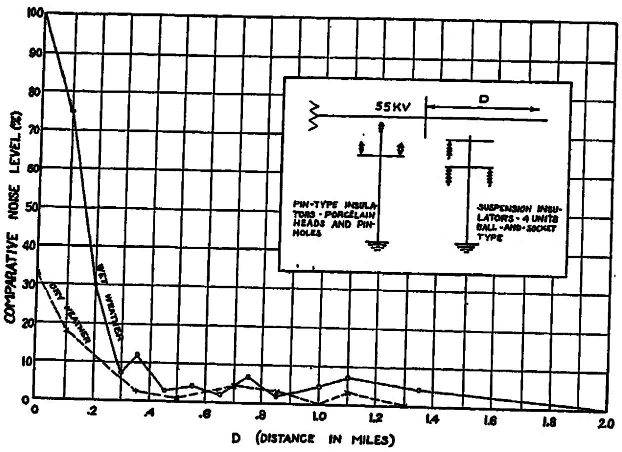

FIG. 1—ATTENUATION OF INTERFERENCE ALONG A TRANSMISSION LINE

the distances to which interference will travel before it is reduced to a non-interfering level, and to show the effect of overinsulation. The observations were made on a 55-kv. line, one mile of which is constructed with pin-type insulators, and the remainder, about 20 miles, with ball-and-socket type suspension insulators.

The origin of the curves is taken at the point where the two types of construction join, and the abscissas are measured from that point along the section using suspension insulators. The ordinates are measured by means of a milliameter coupled to the output circuit of a superheterodyne receiver through a transformer. Although the readings of this meter have no absolute value, their significance becomes apparent when it is known that signals from a 5000-watt radio broadcasting station 75 miles away could not be heard with noise levels of ten per cent or more. At ten per cent the signals were about equal in intensity to the interfering noise. At five per cent the signals were stronger than the interference. With a zero-reading on the meter the interference was not objectionable, although it could still be heard along with the signals from the broadcasting station.

The readings for the upper curve were taken during a rain-storm. The lower curve was taken about thirty minutes after the storm ceased. In the case of the upper curve, a slight amount of interference could still be heard at a distance of four miles, which was attributed to the effect of rain on the suspension insulators.

The curves of Fig. 2 are similar to those of Fig. 1. These curves show the attenuation of radio interference at right-angles to a 55-kv. line for two conditions, (1) with no distribution circuits to radiate the disturbance, and (2) with distribution circuits paralleling the 55-kv. line and connected to other circuits at right-angles to the 55-kv. line. The latter condition is one which occurs frequently in cities and towns, but no way of overcoming it has been devised yet. The most effective method of minimizing this kind of radio interference is the elimination of the interference at its source. In many cases, however, the cheapest remedy for the situation may be the use of radio-frequency choke coils inserted in the distribution circuits where they leave the high-voltage line. Standard lightning-arrester choke coils have been tried, but were not successful because their inductance is too low. One company is successfully preventing radio interference on high-tension lines from following its telephone circuits by inserting choke coils in the telephone leads at points where they leave the high-voltage lines. Another company is experimenting with carrier current choke coils, and still another one is trying specially constructed choke coils of about 0.5 millihenry inductance. No reports are available on these tests, however.

CONCLUSIONS

Radio interference is one of the problems which must be considered in future insulator designs. On pin-type

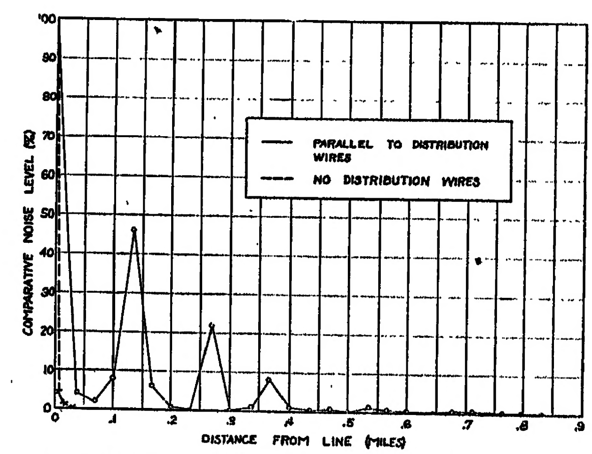

FIG. 2—ATTENUATION OF INTERFERENCE PERPENDICULAR TO A TRANSMISSION LINE

insulators, corona and brush discharges can be eliminated by proper design of the petticoats, by using metal-coated or metal-capped heads, by using metallic threads in the pin-holes, and in some cases, by using a special glaze on the head and in the pin-hole. Suspension insulators can be improved by changing the design of the cotter key in the clevis type, by eliminating discharges between the links and the porcelain in the link type, and by redesigning all arcing horns to eliminate discharges at the ends. The corona-discharge point on cap-and-pin insulators can be raised by proper

design of hardware, by elimination of sharp points, by insuring adequate clearances at the cap and the pin, and by making the shape of the porcelain conform more closely to the lines of electrostatic flux.

Existing pin-type insulators present the most difficult problem of all. Copper mesh placed under the tie-wires has proved fairly successful in eliminating discharges at the head of the insulator, but experiments are still being made to discover a process which can be easily applied, is not too expensive, and which will stand up under operating conditions during the life of the insulator.

Radio interference from line insulators will always be a problem, because corona and brush discharges occur so readily on high-voltage equipment. Much work has been done to minimize this type of disturbance, and more is contemplated. Adequate maintenance and good construction are essential to the solution of the problem, but the greatest needs are for improved designs and continued experimenting.

Discussion

R. J. C. Wood: At Redondo Beach we have a number of insulators hanging up under tests where they may become as dirty as possible with ocean spray and fog. They are not cleaned at all; they are left to accumulate all the spray and dirt that will come. Several times we have tried to detect radio interference from that lot of insulators. There are 16 strings of insulators, of which 3 are post assemblies and the rest are suspension, including 2 dead ends, all under test at 150 kv. to ground. We have never been able to find any radio interference although the insulators are visibly sparking over underneath around the pin of each when the air is damp. So it seems that there might be something more involved than just the design of the insulator string itself; possibly the attachment of a long line with its inherent capacity is necessary to form an oscillating circuit which would give rise to radio interference.

J. P. Jollyman: The experience in respect to radio interference of the several companies operating transmission systems on the Pacific Coast seems to vary considerably. Apparently the greatest difficulty exists in the regions having the heaviest rainfall and hence the cleanest insulators. Less difficulty seems to be experienced in the regions having less rain and a longer dry but partly foggy season. Under these conditions dirt accumulates along an overstressed leakage path and becomes so firmly attached from the effect of leakage currents that a conducting path is built up which is not removed by rain. This conducting path reduces the arcing at overstressed points and apparently reduces the radio interference.

H. N. Kalb: In connection with the bushing that Mr. Jollyman spoke of, we have had the same trouble with arcing between the conductor and the inner portion of the bushing surface and we have installed a screen, using either copper screen or galvanized-iron screen wire, attaching it to the upper part of the conductor, the screen being allowed to spread out and make contact with the inner surface of the bushing throughout the entire length.

With pin-type insulators, we have a great deal of that same trouble that was described in Mr. Van Atta's paper. We use both three-piece and four-piece pin-type insulators, and have found nothing as yet that would clear up the interference entirely. We have tried, in an experimental way, using both the copper gauze that was mentioned in the paper, and screen and different materials of that kind.

So far as the suspension insulators are concerned, we have made some tests on them and find very little interference, if any. I wish to emphasize the word "if" for this reason: We have lines with different sized conductors on which we have found that the noise was of different volume on the different lines. On a 110-kv. line with 7 units in suspension, a line having 0000 aluminum wire was much more noisy than a line of the same voltage with a conductor of 397,530-cir. mil aluminum. Also we arranged for a field test by connecting one of those lines to one unit in the generating plant, starting in with zero voltage and building it up and then lowering it, and at the same time taking a reading of the noise level. We found that the line which ordinarily operated at 120,000 volts still had points of visible corona, at 100,000 volts. Those were few and scattered, of course, but appeared even on the arcing horns. We still had noise at a voltage as low as 70,000 volts. Contrasting with that, we completed a line to operate at 70,000 volts, which had 397,500-cir. mil aluminum conductors, and from the radio interference standpoint, that is probably the most quiet line on which we have ever made any tests.

I simply wish to make that statement because probably a great deal of our trouble is due not to the insulators alone, but to the size of conductors and the voltage impressed on them.

Bradley Cozzens: I was very much interested in the fact that the authors brought out the problem of voltage distribution on insulator strings. With dry insulators, the values which were given are undoubtedly correct. However, on the Pacific Coast, we always find fog, and with the fog comes a wetting of the insulators, and a very marked change in the voltage distribution from that which is found in dry weather. A good example of this changed distribution is the 9- or 10-unit string on 110,000-volt lines, in which two units of the string may be carrying 90 per cent of the applied voltage. Thus there is in excess of 30 kv. on each of the overstressed units. This is made evident by sparking over the under side, and occasionally over the top surfaces of these units. These static sparks develop at times into an arc discharge. At this time the current is limited only by the wet resistance of that portion of the string which is not partially short-circuited by the arcs.

I should like to ask Mr. Van Atta if he has experienced this arc condition, and if so, how serious it is from a radio interference standpoint.

I should like to stress this point further, that other voltage distributions than those normally assumed for dry conditions practically always exist on wet insulator strings, and should be borne in mind when considering interference as caused by line insulators.

F. B. Doolittle: I was interested to note that Mr. Jollyman brought up the subject of radio interference caused by bushings because we have experienced trouble from 66-kv. transformer, oil-switch, and wall-type bushings. These particular bushings consist primarily of a central porcelain tube, the 1-in. bore of which is of considerably larger diameter than the bare copper conductor which passes through it. Consequently it was necessary for the charging current of the porcelain to jump the air-gap between the conductor and the porcelain. This sparking not only caused radio interference but also broke down the air and caused the formation of cupric nitrate on the copper lead. The cupric nitrate was formed in such large quantities in some of the oil-switch bushings that it dropped to the bottom of the switch tanks and ate holes through them, causing oil leaks which led to the discovery of the trouble.

We found that a very simple remedy for this trouble is to insert a split brass sleeve the full length of the hole through the bushing which makes close contact with the porcelain. The sleeve consists of 24-gage brass tubing of slightly larger diameter than the bore of the bushing, the tubing being split lengthwise so that it springs tightly against the porcelain when inserted in the bore. One end of the sleeve is, of course, bonded to the conductor.

In regard to radio interference from line insulators, the Southern California Edison Company is particularly fortunate in that most of the lines are considerably over-insulated. This over-insulation is necessary because of the accumulation of dirt on the insulators during the dry season which would otherwise cause flashovers in fog. Five suspension units are used on most of our 66-kv. lines, which results in such a low voltage stress per unit that no radio interference is produced under ordinary conditions.

We operate a few miles of 33-kv. line on pin-type insulators and have looked for radio interference on them but so far have found none traceable to the insulators. This seems surprising in view of the possibilities for interference with this type of construction as pointed out in the foregoing paper.

Our 11-kv. and 16-kv. lines are in general free from radio interference, I believe largely due to the fact that the insulators used are rated at considerably higher voltage than that on which they are operated.

H. T. Plumb: I was interested to hear the opinion that only clean insulators give radio interference, and that western lines do not interfere. The line of which the gentleman spoke is unknown but there is a line at about 110 kv. between here and San Diego which does interfere. I can vouch for the fact that there is so

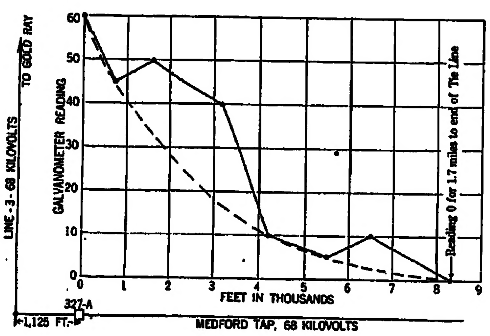

FIG. 1—RADIO INTERFERENCE READINGS

Taken along the Medford Tap of Line 19, 12-21-28, beginning at Sw. 327-A, using radio frequency galvanometer with radio test set. Lapp insulators, 66 kv. No. 6173 had been previously re-tied beyond O. C. B. No. 327-A, using copper web under the tie wire. The web reduced the readings to zero within a distance of 8300 ft. from the switch, and readings remained 0 for 1.7 mile to end of single pole line at junction with 2-pole line insulated 130 kv. and operating at 68 kv.

Started taking readings at Sw. 327-A at 9:20 A. M., arrived at end of 130 kv. line at 10:45 a. m.

much noise from that line, not only radio noise but real sound noise, that it once woke me up in the middle of the night. The line voltage may have increased in the night, or sea fog may have deposited on the insulators so that there was actual arcing between petticoats. An engineer who lives in San Diego and whose home this line passes stated that it causes excessive interference. He has purchased a $600 radio instrument which is practically worthless. He lives within three blocks of that line.

R. S. Daniels: A serious situation at Medford, Oregon, has been remedied by the use of heavy copper braid on pin-type insulators used on 66-kv. wood-pole lines. Seven miles of line have been retied, using not gauze, but a pad of heavy copper braid, No. 4 B & S gage, placed under the tie wire.

Fig. 1 shows relative attenuation along the 3¼-mi. section of line where the braid was used.

We have found that the disturbance originating from discharges between the tie wire and the procelain is greatly affected by (1) rain or snow, (2) clouds, (3) temperature of the air, (4) time of day. The first two are probably due to humidity. Noise is at its worst in hot weather and least in either rainy or cloudy weather.

Fig. 2 shows relative change in noise level throughout the day between the hours of 7:00 a. m. and 10:00 p. m., which shows much more disturbance during clear weather than cloudy. The copper braid as used at Medford for over a year has reduced the noise level to a point which gives practically no interference to radio sets which are near the 66-kv. wires, or near distribution lines, part of which have been carried on the same poles with the high-tension wires.

Fig. 3 shows the application of the braided pad.

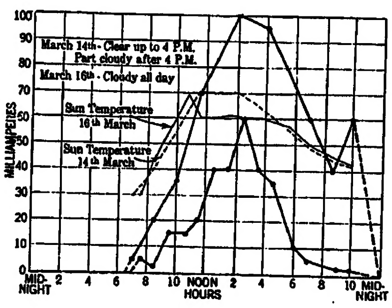

FIG. 2—RADIO GALVANOMETER READINGS AT MEDFORD SUBSTATION

R. L. Binder: (communicated after adjournment) The authors have undoubtedly grasped the essential features of the cause of static on insulators and bushings, but they do not give any information on methods for overcoming the difficulty nor have they mentioned other important considerations in connection with brush and corona discharge on high-tension lines. Not only do corona and brush discharge affect radio transmission but by the generation of ozone, they cause rapid deterioration of insulation and also a high rate of oxidation of conductors.

As far back as 1912, the writer was brought into contact with this condition on what were then considered high-voltage transmission lines and was able to overcome some of the difficulties by cementing metal foil to various parts of high-tension insulators. Such methods, however, did not afford permanent means for overcoming the trouble, because with the breakdown of the cementing medium, part of the foil would separate and that which remained attached to the insulator would increase the static discharge.

FIG. 3

We have called attention to the use of sprayed molten metal coatings on various parts of petticoat insulators and insulator bushings and in every instance where such coatings have been used, entirely satisfactory results have been obtained.

The accompanying report shows exhaustive tests which were made on porcelain bushings.

Sprayed molten metal coatings of lead, tin, zinc, or copper, or combinations of them, have been used with equal success. Where it is desired to place them on the glazed parts of insulators, such surfaces are first sand-blasted and a permanent bond of the sprayed molten metal is readily secured. On clean unglazed surfaces, no sand-blasting is necessary.

The cost of applying the coating is entirely within commercial limits.

Tests on Porcelain Bushings. A series of tests was made to determine a satisfactory method for decreasing the static leakage on some bushings used in circuit breakers. These bushings illustrated in Fig. 4 were used on 2000-ampere circuit breakers. They were normally subjected to a stress of 7700 volts to ground. In the test at 60 cycles, voltage was applied across the brass collar of the bushing and the bus bar through the bushing. The voltage was increased gradually from zero to a value at which static appeared and sometimes to flashover.

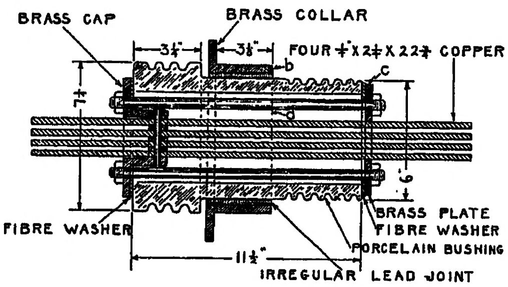

FIG. 4—BUSHING AS RECEIVED FROM FACTORY

The first appearance of static occurred between the through-bolt and the inside cylindrical surface. See (*a*) on Fig. 4. As the air gradually became ionized the static spread and flowed very violently between the main copper conductor and the inside cylindrical surface. When the air within the bushing became entirely ionized and the voltage had increased, static occurred about the alloy fill. With increased voltage the static at (*a*) became violent and gradually crept over the porcelain causing a breakdown at 52,000 volts.

Voltages at which static occurred.

Audible..........	8000 to 9000
Visible inside.....	13,500 volts
Visible outside....	19,000 volts
Flashed over.....	52,000 volts

Methods of Eliminating Static. 1. Filled bushing with steel wool and poured a ring of compound consisting of beeswax and rosin over the visible ends of the metal alloy between bushing and sleeve.

Results—Satisfactory if wool is properly packed.

2. Filled bushing with beeswax and rosin.

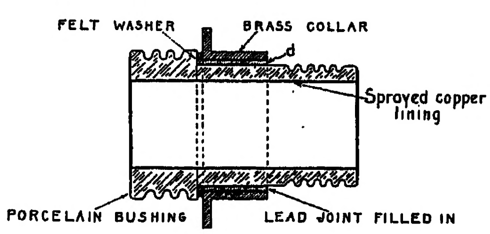

FIG. 5—BUSHING WITH SPRAYED COPPER LINING

Results—Static eliminated until 12,000 volts was reached. Then it appeared on outside from porcelain to metal alloy.

3. Bushing filled with compound. Metal alloy covered with compound.

Results—Very satisfactory. No static at 25,000 volts. Not considered because flexibility of bushing was destroyed.

4. Painted inside of bushing with aluminum paint. Alloy covered with porcelain.

Results—Static at 15,000 volts. Not considered because aluminum paint flaked off.

5. Sheet-metal tube placed inside of bushing and alloy covered with compound.

Results—Very satisfactory. Not considered because method was thought undesirable.

6. Brass through-bolts removed and bakelite substituted, no compound used.

Results—Static occurred at 9000 to 10,000 volts.

7. Inside of bushing coated with 0.006 in. of sprayed molten copper. Alloy covered with compound.

Results—Static occurred at 16,000 volts. Flash point reduced to 46,000 volts. This method adopted to eliminate the static on these bushings.

The inside of the bushing was sand blasted and cleaned. Next a coat of lead 0.004 in. thick was put on to provide a proper base. Over the lead a coat of copper 0.006 in. thick was sprayed. This metal coating is firm and will not flake or peel off. The work was done by the Metals Coating Company of America, at Philadelphia.

Since discovering static on the FH9 bushings, tests were made with a compact superheterodyne radio set on various other types of bushings and the results indicated various amounts of static on practically all of them. This radio set is moved slowly along the compartment doors and the static is picked up even though very slight.

Further tests were made on an untreated bushing and on treated bushings. The results of these tests were as follows:

Specimen tested	Voltages			Remarks
	Audible	Visible	Flash-over	
(Fig. 4) Untreated.....	8,000	11,000	52,500	Discharge first became visible at *a* between the bus copper and porcelain bushings. This discharge gradually increased until flashover occurred from *b* to *c*.
(Fig. 5) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. With irregular lead seal.	8,500	14,000	...	Visible discharge took place from irregular lead seal to porcelain bushing at *d*. No discharge audible or visible inside bushing.
(Fig. 5) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. With lead seal smoothed off.	10,000	17,000		Visible discharge at *d*. No discharge inside porcelain bushing.
(Fig. 6) Inside of porcelain bushing coated with sprayed molten lead 0.006 in. thick. Covered with sprayed molten copper 0.006 in. thick. Specimen No. 1, end of lead seal covered with insulating compound.	16,500	29,000		A very slight visible discharge occurred at *e* between collar and porcelain bushing.
(Fig. 6) Inside of porcelain bushing coated with sprayed molten lead 0.004 in. thick. Covered with sprayed molten copper 0.006 in. thick. Specimen No. 2, with end of lead seal covered with insulating compound.	15,000	29,000	45,700	A greater visible discharge occurred at *c* and gradually increased until flashover occurred from *e* to *f*, *i. e.*, from collar to end plate.

Conclusions. The results of the tests brought out the following points:

1. Application of sprayed molten metal coatings on the inside of the porcelain bushings transfers the leakage from the inside to the outside of the insulator. It also slightly increases the value at which leakage becomes audible, but materially increases the stress on the porcelain bushing.

2. Smoothing off the lead seal between the bronze collar and the porcelain bushing on one of the sprayed types definitely increases the resistance to audible leakage.

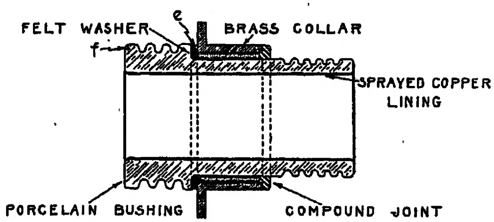

FIG. 6—BUSHING WITH SPRAYED COPPER LINING AND COMPOUND-FILLED JOINT

3. Removing some of the lead seal, and replacing it with an insulating compound, and smoothing it over the entire end of the brass collar, appreciably increases the resistance to audible leakage and transfers the discharge to the large end of the brass collar. Under these conditions, audible leakage occurs at a minimum voltage of 15,000 volts, which is about twice the normal voltage stress of 7700 volts to which these bushings are subjected.

4. The greatest safety factor is therefore obtained by coating the inside of the bushing with sprayed molten metal, and finishing off the end of the lead seal with insulating compound in such a manner as to completely cover the small end of the brass collar.

E. Van Atta: Regarding the voltage on strings of insulators on 220,000 volts, I gave only the maximum voltages. The paper takes care of that; that was given as 23,000 volts without grading rings, but with these it is down to 15,000 volts.

Now regarding dirt and moisture on insulators: There is a question as to whether the distribution of voltage over the insulators isn't changed by these factors. It certainly is. And, as a matter of fact, all of our experience has shown that during wet weather conditions of reception are very greatly improved along high-voltage lines.

In connection with whether a certain line gives interference or not, I think we have to take into consideration the location of that particular line with respect to the broadcasting stations to which you happen to be listening. We know that if a station has a signal strength 100 or 1000 times greater than the disturbing field strength that we are going to get reception and there isn't any radio interference on that line *in that particular location.* If we moved the same line out where we had to reach out 1000 mi. to get reception, it would be as bad as any of the others.

The condition of corona on wires may have something to do with interference along a line. In fact, there are a great many things outside of insulators that have a lot to do with radio interference.

Regarding bushing trouble, we have had a great deal of that. In one instance, on a 66,000-volt bushing, we filled the bushing with compound. In other instances on 25,000-volt transformers with hollow bushings, we have simply wrapped the wire running through the bushing with 10 or 12 thicknesses of Empire tape and this has taken care of the trouble and relieved the radio interference. Incidentally, that same idea may be worth something on pin-type insulators.

Spray and Fog Tests on 220-Kv. Insulators

BY R. J. C. WOOD[1]

Associate, A. I. E. E.

Synopsis.—To determine insulation for an outdoor 220-kv. station on the coast subject to ocean spray, an insulator test rack was installed at Redondo, California.

Ten types of insulator, including widely different designs, were tested continuously for two years and a half at 150 kv. to ground. Comparative results were obtained by adding or subtracting units in suspension strings until an equality against arc-over was approximated. Ninety arc-overs occurred.

The surface leakage resistance was found to be a fair index of the resistance to arc-over under salt spray conditions. The shape of the insulator made no difference as long as the total surface resistance of the string remained the same.

The surface resistance is that calculated upon the assumption of a uniform conducting coating upon all the exposed surface of the insulator and is the line integral of distance divided by circumference along the shortest surface path from cap to pin.

Accidental differences of conditions are such that one insulator string would not consistently arc-over in preference to another unless its surface resistance were less than 80 per cent of the other.

Suspension strings having a total surface resistance of 11.0, using inch units, were found satisfactory for a steady 150 kv. to ground under the conditions at Redondo.

A spray method of cleaning insulators while energized was devised.

Introduction

In the latter part of 1926 it was seen that it would soon become necessary to decide upon the kind of insulation to be used in the Southern California Edison Company's 220-kv. outdoor station that was to be built at Long Beach, on the coast south of Los Angeles.

A test rack was therefore set up at Redondo on the coast, the location being chosen as one of the most subject to ocean spray and fog upon the system, and where considerable insulator trouble on both 66-kv. and 16-kv. lines had been experienced.

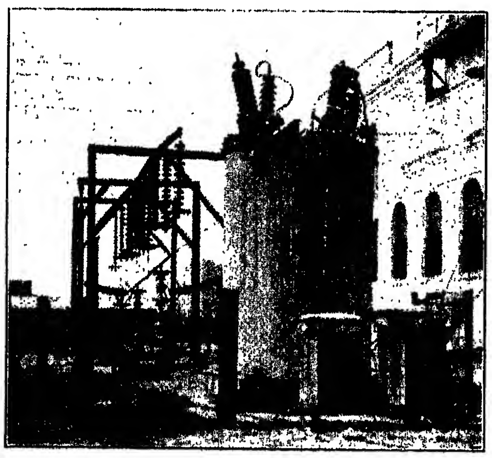

Fig. 1—Test Rack, Energizing Transformer, and Two Small Transformers Used as Reactors. Looking North

Climatic Conditions

The storm winds are westerly and drive the spray from the ocean surf directly into the test rack, the accumulation of salt upon the insulators having been such at times that during the heat of the day small crystals of salt have been observed scattered all over the surface of the porcelain. At night the deposition of moisture upon the insulators is frequently sufficient so that they drip and the sandy soil underneath is all pock marked from the dropping water. In addition to the salt deposit there is a certain amount of dust and sufficient soot to blacken any rag used for cleaning.

The time of year during which arc-overs are most prevalent is from March or April until the first rains of the season, which may come in September or October.

Description of Apparatus

The rack illustrated in Figs. 1, and 2, was situated about 500 ft. from the ocean front. The pipe bus was energized to 150 kv. to ground.

Electrical connections were as in Fig. 3, the two 150-kv-a. banks of transformers in series with the 4500-kv-a. transformer being used as reactors to limit the short-circuit current to 10 amperes over an insulator and 100 amperes on the station bus.

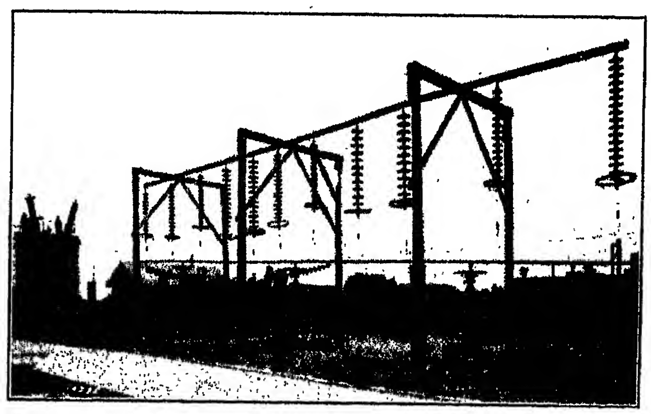

Fig. 2—Test Rack. Looking Southwest

To indicate which of the insulator strings had arced-over, a one-ampere enclosed fuse was connected between each insulator string and the bus. These fuses were further protected against weather and corona by short lengths of one-inch pipe and may be seen in Figs. 1 and 2.

The types of insulator tested are shown in Fig. 4;

1. Research Engineer, Southern California Edison Co., Los Angeles, Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.

some of their physical constants in Table I. The quantity called "Surface Resistance" is not any measured resistance, but is the calculated surface leakage resistance from cap to pin of a single insulator unit, assuming the exposed porcelain surface to be uniformly coated with a conducting layer. Should the conducting layer have a resistance of one megohm per square inch, then the figures of Table I give the surface resistance from cap to pin in megohms.

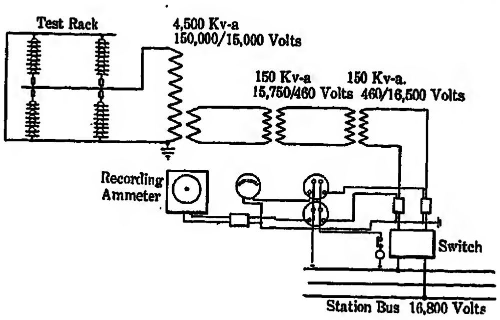

FIG. 3—DIAGRAM OF CONNECTIONS BETWEEN STATION BUS AND TEST RACK

The rack was kept energized both day and night whenever possible; an arc-over would cause the relays to open the main 16-kv. switch; the operator would at once close the switch again; if upon the third trial the arc-over still persisted the switch would be left open until the next day. Arc-overs practically always occurred during the night when fog or dew was heaviest.

PROGRAM OF TESTS

During the period from January 1, 1927, to June 1, 1928, a number of rather long suspension strings was under test, no changes being made except to disconnect two short strings of 13 Type *A* and 13 Type *D* which arced-over.

The strings under test during this period are detailed in Table II. They were all washed by hand on February 9, 1927. 6-*E* and 6-*J* were washed immediately after each arc-over, and 5-*J* was washed frequently as described later.

Beginning June 1, 1928, the program was changed. Strings 8-*E*, 7-*E*, 6-*E*, were removed (the number and letter designating the number of units of a certain type).

The other types in service had the effective number of units in a string reduced by short-circuiting any required number of units, at the upper end of the string, with wire.

The general practise was then followed of adding a unit, by moving the short-circuiting wire, on any one string after it had arced-over on two separate days. This wire device enabled units to be added or subtracted without handling the units and changing their surface condition.

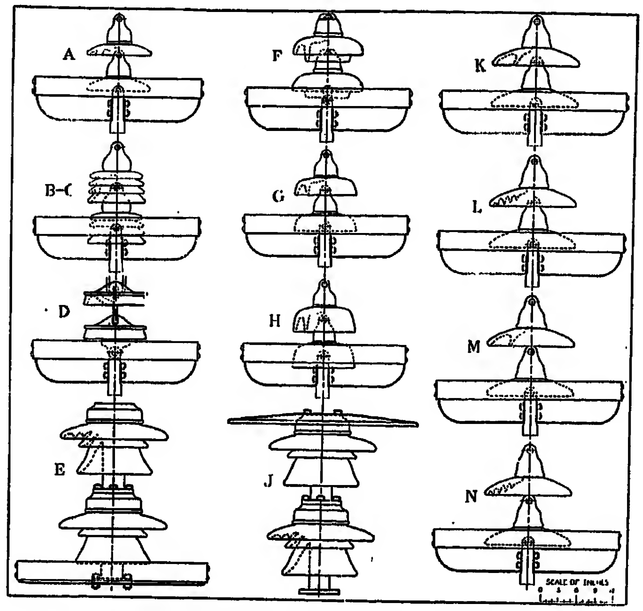

FIG. 4—TYPES OF INSULATOR UNDER TEST

It was expected in this way to arrive gradually at an equality in the different strings.

Types *H* and *G* were not put on test until October 15, 1928; Types *C* and *F* were added January 10, 1929.

In order to get comparative results, types *C*, *F*, *G*, *H*, *N*, *M*, were all washed by hand on January 15, 1929, so as to have them in the same condition as the recently added types. None of the other suspension strings had

TABLE I
PHYSICAL CONSTANTS OF INSULATORS: INCH UNITS

Type	Diameter	Leakage distance	Surface resistance	Resistance per inch leakage	Axial length per unit	Resistance per axial inch
A	10	10.75	0.651	0.0605	5.75	0.1132
B	9	20.0	1.062	0.0531	6.5	0.1634
C	9	18.25	0.955	0.0523	6.5	0.1468
D	10	11.0	..	..	5.37	..
E	17	33.0	1.163	0.0352	14.5	0.0802
F	11	16.5	0.811	0.0492	5.75	0.1411
G	10	13.12	0.715	0.0545	5.75	0.1244
H	10	15.5	0.837	0.0540	5.75	0.1455
J	17	33.0	1.163	0.0352	14.5	0.0802
K	14	16.5	0.848	0.0514	6.6	0.1285
L	14	19.0	0.908	0.0478	6.6	0.1375
M	14	16.5	0.848	0.0514	8.0	0.1060
N	14	19.0	0.908	0.0478	8.0	0.1135

Note: Resistance is not easily calculated for Type D. From test results it seems to have approximately the same resistance as Type A.

been washed, except by natural rains, since February 9, 1927, and they were now left in that state but reduced in number of units per string and the process of building up to an equality started in again.

On June 15, 1929 the program was again changed and all types, except the posts *J*, had units added until

TABLE II
INSULATOR STRINGS UNDER TEST 1-1-27 TO 6-1-28

Number in string	Type and position	Leakage distance	Surface resistance	Period under test
13	A suspension	140	8.47	1-1-27 to 3-12-27
17	A "	183	11.06	1-1-27 to 6-1-28
15	AA dead end	161	9.77	1-14-27 to 6-1-28
*				
15	AA " "	161	9.77	1-14-27 to 6-1-28
12	B suspension	240	12.75	1-1-27 to 6-1-28
13	D "	143	..	9-23-27 to 2-1-28
6	E "	231	6.98	1-1-27 to 6-1-28
7	E "	231	8.14	" " "
8	E "	264	9.30	" " "
5	J post	165	5.81	" " "
6	J "	198	6.98	" " "
7	J "	231	8.14	" " "
15	K suspension	248	12.72	" " "
12*L* + 3	K "	278	13.43	2-10-27 " "
12	M "	198	10.17	1-1-27 " "
12	N "	228	10.89	2-10-27 " "

there was one more unit in each string than the maximum number that had arced-over at any time.

Arc-Overs

The first period of the test showed that neither the five- nor six-unit post, type *J*, would be satisfactory without periodic cleaning; it was found feasible, however, to spray the five-unit post with water, while energized, without danger of its arcing-over, provided the spraying were done frequently. Cleaning once a week apparently kept this post in good condition. The special spray nozzle used washed practically the entire porcelain surface.

13-*A*, 13-*D* proved inadequate, each arcing over twice. There were six arc-overs on 6-*E* in suspension and three on 6-*J* as a post, in each case the insulator being hand washed immediately after arcing-over. This difference in behavior between post and suspension may have been due to the slight difference in the shielding, or to the cap in one case and the pin of the insulator in the other being at bus potential or, what seems most probable, that at the greater elevation above ground of the suspension string there was a greater wind velocity and more spray and dirt were deposited upon the porcelain; heat radiation would also be greater in the more exposed position and deposition of dew greater,—all of which would render the suspension string more liable to arc-over than the post. The post 5-*J* arced-over four times but not after regular washings were inaugurated. No relative values for the remaining suspension strings were obtained as none arced-over. Altogether there were 17 arc-overs in this period.

From June 1, 1928 to September 30, 1928 there were 30 arc-overs. The first rain of the season occurred October 11, 1928, and no further arc-overs took place until March 4, 1929. From March 4, 1929 to July 19, 1929 there were 43 arc-overs, giving a total of 73 arc-overs from which to analyze the relative performance of the different types of insulator.

Analysis of Arc-Overs

In Fig. 5 each flashover has been plotted with a view to seeing whether the leakage distance might not be the controlling factor in arc-over; if so, the string arcing over should have the least leakage distance of all under test. When this was the case it was plotted as a circle at 100 per cent. When, however, there were one or more strings having lower leakage distances than the one arcing-over, then they were plotted as crosses showing their leakage distances as a per cent of that of the string that arced. Thus in Fig. 5 any type which has many low-percentage plots is apparently not so good as one in which the plots are of a higher percentage, remembering

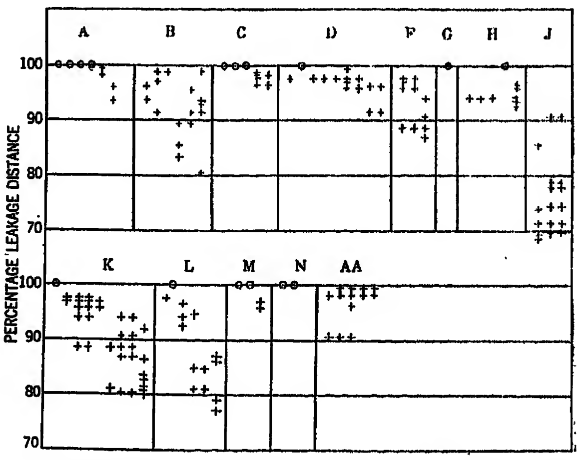

Fig. 5—Comparison of Types upon a Leakage Distance Basis

The insulator string having the shortest leakage distance is not always the one to arc-over. Each cross shows the percentage leakage length of a string that was shorter than the one arcing-over. A circle shows the shortest arcing-over.

that the comparison is not unit per unit, but is based upon strings of equal leakage distance.

It is seen at once that this basis of comparison is not entirely satisfactory. Due to the unavoidable variations in amount of deposit, dew, wind, no two strings of insulators subjected to field conditions would ever behave exactly in accordance with any of their physical dimensions, except by accident. It would, however, be expected that they would average in some relation to some measuring stick, each exhibiting departures on either side of a mean. When these departures from the mean were the same for each, then they would be considered as equal, according to the particular basis of measurement chosen. Extending this argument to a number of different types of insulator, a true basis of comparison will have been found if in such a plot as Fig. 5 all the types exhibit equal divergencies. It is seen at once that Fig. 5 fails chiefly with respect to Type *J*, which by reason of its position should show up

better than all others. Fig. 5 shows it as the worst. The intercomparison of the other types is fair in view of the fact that *C, F, G, H, N, M,* were all washed January 15, 1929, and would be expected to show up better than the others last washed February 9, 1927. It will be found significant that the ratio of surface resistance to

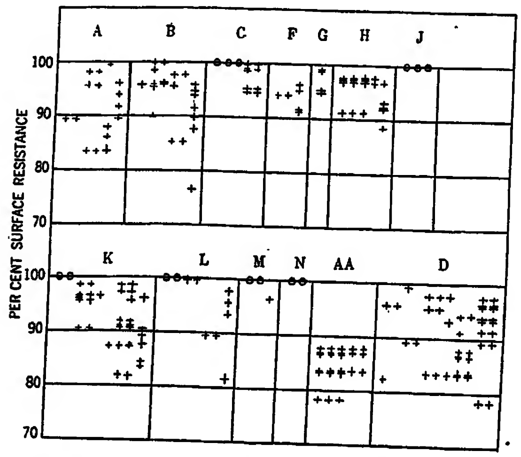

FIG. 6—COMPARISON OF TYPES UPON A SURFACE RESISTANCE BASIS

Each cross shows the percentage resistance of a string that was less than that of the one arcing-over. A circle shows the lowest resistance arcing-over

inch of leakage distance does not vary over a wide range until Type *J* is considered.

In Fig. 6 a plot similar to that of Fig. 5 is shown, the total surface resistance of the string, instead of the leakage distance, being made the basis of comparison.

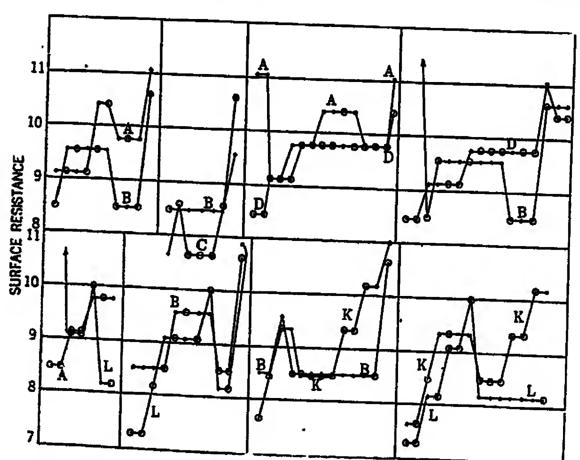

FIG. 7—COMPARISON OF TYPES BY PAIRS UPON A SURFACE RESISTANCE BASIS

The string arcing-over is marked with a circle vertically over or under the one not arcing. Insulators not washed since Feb. 9, '27

Type *D* is given an arbitrary resistance per unit equal to that of Type *A* for reasons referred to later. This plot exhibits a much greater uniformity than Fig. 5. Types *A, B, K, L, AA, D* are practically identical as to the range covered and are all types not washed since February 9, 1927. Types *C, F, G, H,* also have about the same range; *M* and *N* are restricted in range but the number of observations is small for each. The same qualification applies to type *J*; however, *J* is now in its proper place, not having arced-over unless it had the lowest resistance, which is as it should be considering its preferred position near the ground.

As a further test of the supposition that the surface resistance is a comparative measure of the resistance to arc-over, a direct comparison between types, taken in pairs, covering the whole period January 1, 1927 to July 19, 1929 is given in Figs. 7 and 8.

Comparing for instance Types *A* and *B*, each arc-over that has occurred upon either one of these is plotted, showing in the same vertical line the surface resistance of the two strings, the one that arced-over marked with a circle, and the one that did not, with a dot. Drawn lines connect points of the same type and do not represent any relation between coordinates.

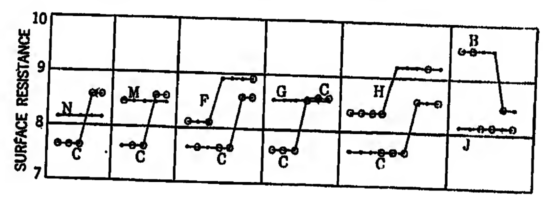

FIG. 8—COMPARISON OF TYPES BY PAIRS UPON A SURFACE RESISTANCE BASIS. INSULATORS NOT WASHED SINCE JAN. 15, '29

Type *D* has arbitrarily been assigned such a resistance per unit as would make it best fit the comparisons *A-D* and *D-B*, *A* and *B* being radically different designs. This arbitrary resistance of *D* turns out to be the same per unit as the calculated value for *A*.

If there were none of the accidental variations previously referred to and the surface resistance were an exact measure of the arc-over resistance, then the circle points would always be on the lower line. This is not the case, considering those pairs of points where the higher resistance string has arced-over. The amount of the discrepancies is shown in Table III.

TABLE III
PERCENTAGE DISCREPANCIES OF FIGS. 7 AND 8

Pair of types considered	Average difference in surface resistances as per cent of the greater	Period of test
A–B	5.38	1–1-27 to 7-19-29
B–C	7.07	" " "
A–D	6.15	" " "
D–B	2.76	" " "
A–L	4.17	" " "
B–L	4.40	" " "
B–K	8.60	" " "
K–L	8.22	" " "
B–J	0.00	" " "
N–C	3.72	" " "
M–C	1.28	1-15-27 to 7-19-29
F–C	5.80	" " "
G–C	0.12	" " "
H–C	8.23	" " "

It will be noted that the discrepancies are not large after all, considering the nature of the original data, and it is certainly impossible to assign to any one type

rather than another any materially greater liability to arc-over when equal surface resistances of each are taken and exposed to the same conditions.

It therefore appears that the surface leakage resistance is a close measure of the ability of these types of insulators to stand up under such conditions as are found at Redondo and that there is no particular virtue in one shape over another, except in so far as it may afford more surface resistance and enable a fewer number of units to provide the total required.

There is a limit to the reduction in number of units per string imposed by ordinary dry and wet arc-over requirements and the danger of puncture when too few thicknesses of porcelain are used between line and ground. It would seem conservative to satisfy the ordinary line conditions as to number of units and then choose the type and perhaps greater number of units which will furnish the necessary surface resistance to suit the locality at the minimum of cost for both insulators and supporting structures.

The final results of the elimination contest are shown in Table IV.

TABLE IV

LIMITS REACHED IN ARC-OVER, LEAKAGE, AND RESISTANCE

Type	Max. number arced-over	Min. number not arced	Leakage arced-over	Distance not arced	Surface arced-over	Resistance not arced
A	16	17	172	183	10.41	11.06
B	10	11	200	220	10.62	11.69
C	9	10	164	183	8.59	9.55
D	16	17	176	187	10.41	11.06
E	7	8	231	264	8.14	9.30
F	11	12	182	198	8.92	9.73
G	12	13	158	171	8.58	9.30
H	11	12	171	186	9.21	10.04
J	7	..	231	..	8.14	..
K	12	13	198	215	10.17	11.01
L	11	12	209	228	9.99	10.89
M	10	12	165	198	8.48	10.17
N	9	11	171	209	8.17	9.99

Note. Resistance per unit of "D" assumed equal to that of "A".

It is seen that strings having a surface resistance of from 9.99 to 10.62 have arced over, these strings having gone through the whole period of the test from 1-1-27 to 7-19-29 without being artificially washed, but that the strings washed 1-15-29 had in competition with them arced-over resistances of from 8.17 to 9.21, showing to some extent quantitatively how the washing done by natural rains compares with careful artificial cleaning. It further seems that a string with surface resistance of 11.0 will satisfactorily insulate against a steady 150 kv. to ground for three years under climatic conditions similar to those encountered at Redondo.

Acknowledgments are due practically all the insulator manufacturers for their ready response with samples of "fog type" insulators without which it would have been impossible to arrive at such definite results.

Conclusions

1. Insulators may be compared, as to their ability to withstand arc-over under spray and fog conditions, by their surface leakage resistance, calculated as the line integral of length divided by circumference along the shortest surface path from cap to pin.
2. There is no virtue in any particular shape except as it provides surface leakage resistance.
3. One insulator string will not consistently arc over in preference to another unless its surface leakage resistance is less than 80 per cent of that of the other.
4. A surface leakage resistance of 11.0, in inch units, per string, appears sufficient for a steady voltage of 150 kv. to ground with conditions as at Redondo, Calif. On a line, allowance may have to be made for surges.
5. It has been found practical to clean some insulators, while energized, with a water spray and thus use a smaller number of units than would otherwise be safe.

Discussion

G. A. Fleming: The 220-kv. insulators at Long Beach Steam Plant were selected on the basis of Mr. Wood's tests. Six type *J* units are used for the bus supports and 15 type *B* units for the strain insulators. A spray system for washing the insulators while energized was also installed. All of this equipment has now been in service for about 15 months and verifies Mr. Wood's conclusion to a very great extent.

The bus supports have one more unit or 20 per cent more insulation than has been found entirely satisfactory at stations away from the sea coast, but have less surface resistance than Mr. Wood's tests show desirable at Redondo without frequent cleaning. A spray-nozzle system was therefore installed and the insulators are washed once each day from two nozzles placed 10 ft. from the bus supports. The cleaning secured has been very satisfactory and leaves only a small deposit on the under side of the porcelain petticoats to be removed by hand when found convenient.

To determine the factor of safety against arc-over when the washing is being done, a series of laboratory tests was made on insulators which had been covered with sea water and sand. It was found that the bus supports stood 325 kv. without arc-over and the strain insulators in a horizontal position stood an even higher voltage. But the factors of safety on the same strain insulator in a vertical position and on the equipment bushing, were found to be considerably lower. This characteristic of the strain insulators is attributed to the distance between units being so small that a continuous stream of water is formed by the run-off from the spray. The surface resistance of these units is so high that no trouble is expected on the transmission line where washing is impractical, but the added safety of clean insulators is obviously desirable at such an important station and it is now planned to change the vertical strain insulators to type *L*.

The bushings were found to have a low surface resistance which makes frequent cleaning imperative, so they are being washed while energized, even though the concentration of salt in the test covering had to be reduced to 1/10 that of sea water and only one spray nozzle used to stand 325 kv. without arc-over. Sparking is of course more noticeable when washing the bushings than the bus supports, but no trouble has been experienced. Larger bushings will of course be specified for all future equipment.

F. W. Maxstadt: Some dry flashover tests on glass cylinders in electric fields between parallel plates where the electric lines are parallel to the surface of the insulator have been in progress in our laboratory and Mr. Wood's first conclusion suggested that we try wet flashover tests on the same apparatus.

The following r. m. s. voltages were obtained:

	Flashover	Surface resistance on 150-kv. basis
(a) Two-in. long by 1-13/16 in. diameter glass cylinder, treated with three successive coats of sea water dried between each coat.—Dry 25 deg. cent.	12,500	4.2
(b) Same sample with a fourth coat of sea water.—Dry	10,300	5.1
(c) Same sample with 3 coats dried and one wet.	5,000	10.5
(d) Sprayed with fresh water (fine mist) but many times as much water as natural mist and sprayed from 3 sides at once; some salt remaining	7,500	7.0
(e) Spray reduced to half of former amount...	8,300	6.3
(f) Corona and streamers but no flashover; spray in action as in (d)	4,200	12.5

Test (c) is under conditions most nearly duplicating Mr. Wood's worst weather at Redondo and the agreement is quite satisfactory.

The fact that this test is on an insulator of a shape radically different from those used by the author, a shape intended to eliminate some of the uncertainties such as flux refraction and non-uniform surface-current density, strengthens his second conclusion.

Test (d) indicates the factor of safety that may be expected when spraying salty insulator surfaces with fresh water.

The values above given are reproduceable within 10 to 15 per cent. The source of test voltage was a 250-kv., 400-kv-a. transformer with only 15,000 ohms resistance in the high-voltage circuit, a voltmeter coil being used for the readings.

R. J. C. Wood: It may be of interest to bring the Redondo tests up to date.

Referring to Table IV of the paper, string *D* has been increased to 17 units and has subsequently arced over twice. String *G* arced once, was increased to 14 units and has not arced over since. One unit was added to string *H* which now has 13 units that have not arced over. In other respects Table IV remains unchanged.

Mr. Maxstadt's results in the laboratory, giving the same order of results as those obtained outdoors, are very gratifying and important as so much of the difficulty of research work lies in the proper coordination of laboratory results and field experience.

The Sixty-Cycle Flashover of Long Suspension Insulator Strings

BY R. H. ANGUS*

Enrolled Student, A. I. E. E.

Synopsis.—This is a study of the 60-cycle flashover of strings up to voltages of 1100 kv., undertaken at the Ryan High-Voltage Laboratory, Stanford University. Investigation was made of the variations in flashover voltage for similar horizontal and vertical strings, with and without shields and tower members. An attempt has been made to correlate these flashover voltages with the point-to-point and point-to-grounded-plane arc-over voltages established in 1928 at the Laboratory. [1]

INTRODUCTION

THE dry 60-cycle flashover voltage of long strings of cap-and-pin porcelain insulators, is of some importance in the design and selection of the insulation for any particular project. There are authorities who advocate the adoption of a wet flashover as the criterion;[2] but the difficulties which have been encountered in the standardization of a suitable "rain" or "mist" make it inadvisable to accept this as the only test of insulator strings.[3] Further, if Dr. L. B. Loeb's[4] theory of breakdown is established, it may be that power frequency arc-over voltages will be a measure of impulse voltage flashover of insulator strings, provided arcing-rings are designed and fitted to prevent cascading arcs.[5]

In all the publications dealing with the flashover of insulator strings, which the writer has seen, no reference was found to tests on strings in a horizontal position. Judging by the large numbers of strain strings in any high-voltage line, this would appear to be an important omission, which may be filled by the tests on horizontal strings to be described in this paper. Only one article mentioned flashovers of more than 750 kv.[6] Because deviations from a straight line flashover-distance relation only begin to appear above 600 kv., the experimental work was continued up to flashovers of 1100 kv., which is the maximum voltage to ground available at the Ryan High-Voltage Laboratory.

Doubt has been expressed as to the necessity of increasing the number of insulators in strain strings, by one or two, over the number in a normal suspension string. This seems to be standard practise to attempt to overcome the deterioration of insulation due to the accumulation of dirt and the heating effects of sunlight. But the flashover of similar clean strings in the two positions was not thought to be different,[2] although the form of the electrostatic field about vertical and horizontal strings cannot be the same.

THE NATURE OF FLASHOVER

The flashover of an insulator string is the breakdown of the surrounding air, and consequently follows the laws of conduction of electricity through gases, which have been formulated by Paschen, J. J. Thomson, J. S. Townsend, L. B. Loeb, F. W. Peek, and others. The process of breakdown is thought to consist of ionization of the air and disturbance of the electronic orbits, consequent on the applied voltage gradient, till the air attains a conducting or chemically reactive state. When this occurs a sharp spark takes place, the spark having many of the characteristics of a condenser discharge. The power arc immediately follows. In the preparation for breakdown, ionization is dependent on voltage gradient and therefore on the form of the electrostatic field. Previous to power-frequency point-gap arc-overs of above 500 kv., long "streamers" sparks reach out from the electrodes. The air in the paths of these sparks is conducting and their presence must influence the distribution of the field. It is conceivable that their influence is the main cause of the widely varying arc-over values which are observed.[7]

The field about an insulator string is, as is well known, by no means uniform. The equal capacities of the units, as they are in series, give a higher stress at the line end of the string than at any other place. Equalizing shields do much to unify the distribution of stress along a string, but they and grounded tower structures complicate the form of the field, so that the effect of their presence on the flashover of a string can hardly be accurately anticipated for any particular case. All that can be done is to discover the variations in flashover values due to surrounding objects, for some extreme cases.

THE TEST INSULATORS

Only two types of insulators were used in the tests. Both were standard ball-and-socket cap-and-pin porcelain insulaters, whose principal dimensions are: insulator "A", diameter 10 in., pitch 5.75 in.; insulator "B" diameter 10 in., pitch 5.0 in.

It is hoped that the selection of this type of insulator will in no way prejudice the possibilities of other types, including that evolved by Dr. H. B. Smith.[8] Only ring shields at the line end and arcing-rings at the ground end of the strings were used, as arcing horns appear unsatisfactory.[5] The shields were to attempt

*Commonwealth Fund Fellow at Stanford University, Palo Alto, Calif.

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to equalize the electrostatic stress on individual units, and the arcing rings were to insure that the arc clears the string at the ground end. The dimensions are below.

Shields. Single String; a circular torus, internal diameter 22 in. of 2.5-in. circular metal material, mounted from the line clamp so that the central plane of the torus was one inch below the top of the cap of the line unit. The whole shield was in metallic contact with the high-voltage line.

Double String; an oval ring, internal diameters 33 and 20 in., of oval material 1 in. by 0.5 in., mounted in a similar way to the single string shield with the 33-in. diameter in the plane containing the axes of the two strings. The 1-in. diameter of the material was parallel to the axes of the strings.

Arcing-rings. Single String; circular ring, internal diameter 20 in. of 1-in. by 0.25-in. flat material, mounted in metallic connection to ground, the 1-in. dimension parallel to the axis of the string. The ring was level with the porcelain of the ground unit.

Double String; similar in every way to the double string shield.

Flashover voltages of vertical and horizontal strings of both types of insulators, were measured for the following cases:

1. Strings without shields or arcing-rings.
2. Strings fitted with shields and arcing-rings.
3. Strings fitted with shields and arcing-rings, tower structures being present at the ground end of the string.

In each case the nearest object, other than these mentioned above together, with the high-voltage and ground cables was over 18 ft. from the string.

Method of Conducting Tests

As the flashover of any gap is dependent on ionization, the maximum voltage reached before spark-over is the value that must be measured. With an alternating voltage, the required value is that of the crest immediately previous to spark-over. Thus, a satisfactory method of measuring this value must be devised; either the crest value or the wave form must be known, and the use of an oscillograph is obviously desirable. The technique of voltage measurement by means of an oscillographic record of the current through a water resistor, as developed in 1928 at the Ryan High-Voltage Laboratory,[1] proved to be invaluable. This method was used to calibrate the voltmeter coil of the high-voltage transformers, for each type of set-up. as differing capacities to ground and differing corona loads affect the constancy of the voltmeter coil's transformation ratio.

Five separate oscillograph measurements were made for each of a number of typical set-ups. The results so obtained were compared with voltmeter coil readings of other flashovers of the same strings. This led to a calibration curve for each type of string, so that voltmeter coil readings could be used for similar strings of different lengths.

Results were thus achieved more quickly than if an oscillograph had been used for every measurement.

No temperature or pressure connections of flashover voltages were made, as at no time during the tests were the conditions sufficiently far from the standard of 760 mm. and 25 deg. cent. to warrant such connections.

Comparison of Flashover Voltages

There are certain principles which must be accepted before flashover values of different strings may be compared; these are:

1. Flashover values should be referred to the arc-over distance and not to the number of units in the string. The arc-over distance is the length of the shortest path in air which arc can take from the line to the ground end of the string.
2. Comparison of the flashovers of complete strings under working conditions should be made only with each other, or some standard, and not with the flashover value of one unit of the string.[9]
3. The lowest observed flashover is the important value. Proceeding on these lines, an attempt has been made to relate the lowest flashovers of suspension and strain strings with the standards of the point-to-point and point-to-grounded-plane arc-overs.

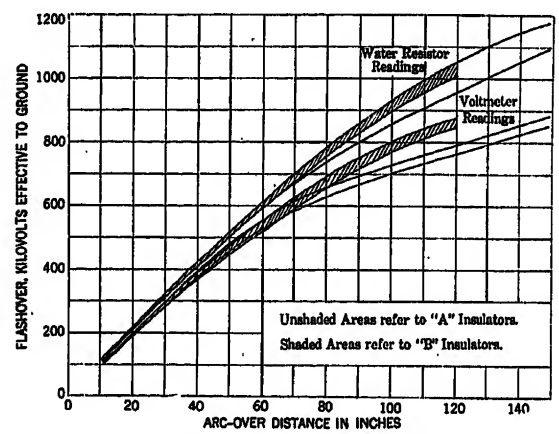

Fig. 1—Flashover of Suspension Insulators, Strain Position, Unshielded

Discussion of Results

As the flashover of a string of insulators to a certain extent is dependent upon the initial state of ionization of the surrounding air, a constant flashover voltage cannot be expected, and the values may be represented rather by an area than by a line curve. This is done in Fig. 1. The areas denote the range within which the flashover of a strain string may occur, for the two types of insulators which were tested. A comparison is also made between the values derived by the water resistor method and the direct voltmeter readings. This shows the necessity for calibration of any particular arrangement of apparatus.

With "B" insulators, the calibration ratio increases steadily with the string length, which is a result of the increasing corona load as the flashover voltages grow larger. With "A" insulators a greater change in the ratio sets in at 550 kv. This is due, first, to the increasing corona, and second, to priming which occurs with more than six of this type of unit. "Priming" is a term applied to the short, snapping sparks over the

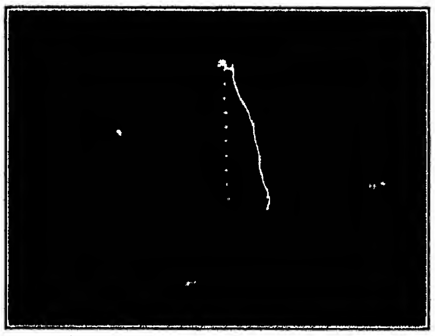

FIG. 2—NON-CASCADING FLASHOVER OF VERTICAL STRING OF 10 "A" INSULATORS

line units, occurring before arc-over. It is the direct translation of the French expression for this phenomenon,[9] and should, in the opinion of the writer, be used in preference to "cascading," which should de-

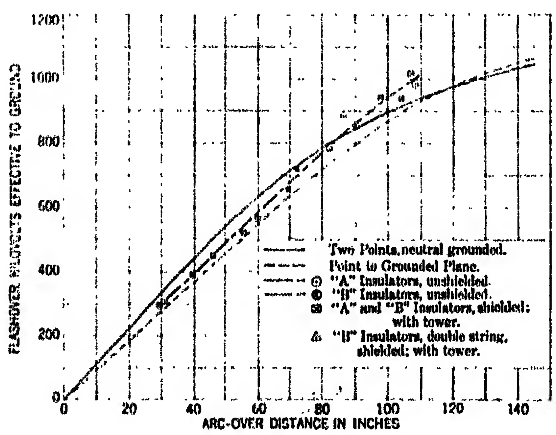

FIG. 3—FLASHOVER OF SUSPENSION INSULATORS, VERTICAL POSITION, LOWEST OBSERVED VALUES

scribe only the type of arc that clings close to the porcelain in its passage from one cap to the next.

LOWEST OBSERVED VALUES

1. Strings in the Vertical Position.

(a). "A" and "B" insulators, unshielded.

In this position, the conductor has a very considerable shielding effect on the string; so much so that no priming took place, and only 108 in. could be arced over with the 1100 kv. available. There was some cascading with "A" insulator strings of above ten units. Fig. 2 is a typical non-cascading arc-over.

(b). "A" and "B" insulators, with shields, arcing-rings, and tower members.

The lowest flashover voltages for the same arc-over distances are very similar to those for unshielded strings; the effect of the conductor is nearly as much as that of the shields in equalizing the stresses on individual units and preventing both priming and cascading. This is especially noticeable with the smaller pitched "B" insulators.

The values for shielded and unshielded strings are so equal that one curve serves for both sets. (Fig. 3.) The curve is approximately midway between the point-to-point and point-to-plane curves; the deviation from this position at above 750 kv. is due to the effect of the capacity-to-ground on a vertical gap, which causes about 20 per cent increase in the arc-over value of a 110-in. point-gap when the lower point is moved from ground level to 15 ft. above it.[1]

In order to discover any effect of the vertical part of

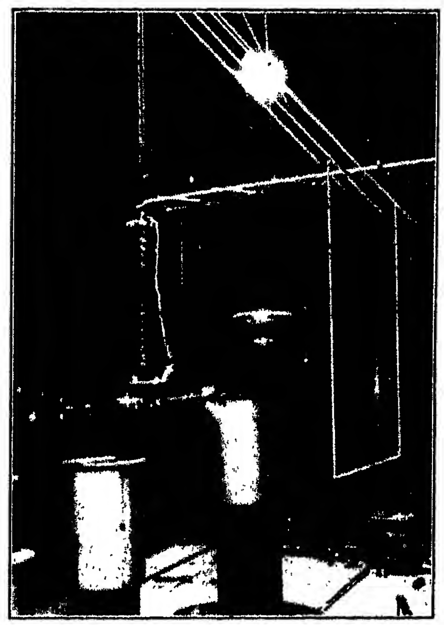

FIG. 4—FLASHOVER OF 20 "B" INSULATORS, WITH SHIELDS AND TOWER MEMBERS IN POSITION

towers on flashover values, a large wire screen was erected 10 ft. 10 in. from the nearest point of the shield of a string of 20 "B" insulators, and the screen was connected to ground. (Fig. 4.) Voltmeter readings of flashovers were taken with and without the screen in place. The averages of the two sets of readings were equal, showing that the voltmeter coil calibrations of the two set-ups were the same. But the lowest observed values were 900 kv. with the screen and 930 kv. without. It is probably safe to infer that the exploring streamer sparks were influenced by the presence of the screen, resulting in a 3 per cent lower flashover. This is barely greater than the limits of experimental error. Consequently it may be said that the important part of the tower, as regards flashovers, is the member at the ground end of the insulators.

The flashover voltage of a double string when

shielded, is sufficiently near to that of a similar single string to assume that they are equal, provided they have equal arc-over distances, (Fig. 3).

2. Strings in the Horizontal Position.

In the horizontal position the conductor provides no shielding effect. In actual transmission lines, the jumper at anchor towers would give some shielding; but it was decided to use an extreme case, as might be found at a terminal point, where the lead to the trans-

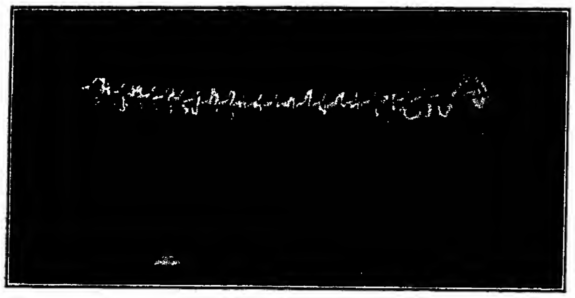

FIG. 5—FLASHOVER OF 25 "A" INSULATORS, STRAIN POSITION

formers or switchgear is in such a position as to shield the insulators but little.

(a) "A" insulators, unshielded.

The lowest flashover voltages of unshielded strings of "A" insulators are mid-way between the point-to-point and point-to-plane values, up to about 750 kv. Above this, both priming and cascading (Fig. 5) become very marked, and the curve runs below those of the two

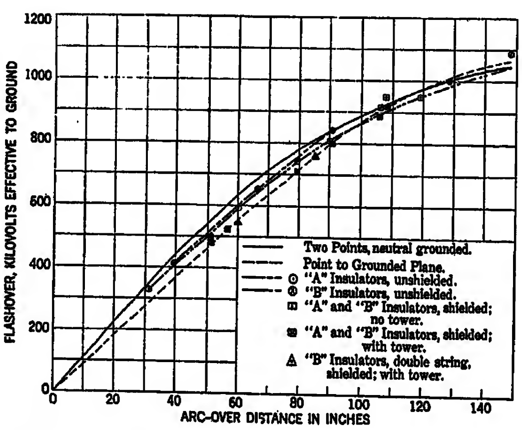

FIG. 6—FLASHOVER OF SUSPENSION INSULATORS, STRAIN POSITION, LOWEST OBSERVED VALUES

standards. (Fig. 6.) It should be noted that 25 "A" units were arced over only because priming and cascading occurred. The flashover of 25 of the closer pitched "B" units was beyond limits of the high-voltage transformers, for with them there was less priming and cascading. (Fig. 7.)

Fig. 8 is interesting, as it visibly demonstrates the need of shields and arcing-rings; corona from the high-voltage lead has shielded the first nine units, but cascading has occurred on the ground unit.

(b) "B" insulators, unshielded.

The smaller amount of priming with "B" insulators results in a higher flashover for a given arc-over distance than with the "A" insulators, although there is hardly any difference between the flashovers of the two types for strings of less than 15 units.

(c) "A" and "B" insulators, with shields, arcing-rings, and tower members.

Fig. 9 shows a typical arc-over. An arc to the tower sometimes occurred, and the flashover was frequently below the string but in every case the arc cleared the units.

The flashover voltages were the lowest of all those

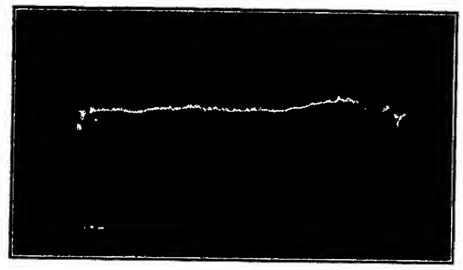

FIG. 7—FLASHOVER OF 22 "B" INSULATORS, STRAIN POSITION

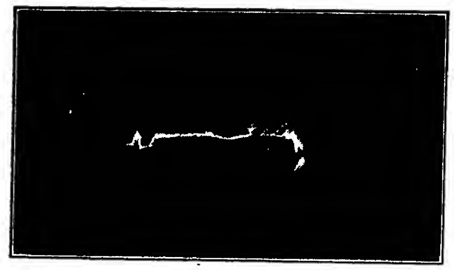

FIG. 8—FLASHOVER OF 10 "A" INSULATORS, STRAIN POSITION

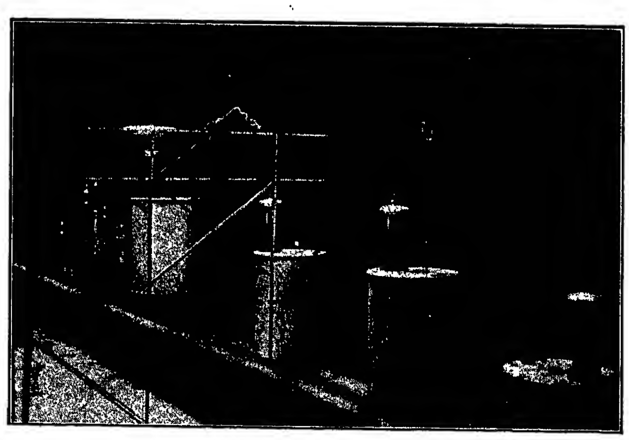

FIG. 9—FLASHOVER OF 20 "A" INSULATORS, WITH SHIELDS AND TOWER MEMBERS IN POSITION. WATER COLUMN RESISTOR IN FOREGROUND

measured. They agree very closely with the point-to-grounded-plane values, as might have been anticipated from the position of the high-voltage lead with respect to the grounded tower.

CONCLUSIONS

1. Variation in Pitch. With strings in any position which are shielded (either by the conductor or by

shields) a 15 per cent variation in pitch does not affect the arc-over.

With strings which are not shielded cascading and priming may result on an increase in pitch. This will lower the flashover value.

The 5-in. pitch of the "B" insulators seems to be as large as a 10-in. diameter unit will stand without cascading. This is in close agreement with the results of G. Viel[9] for cap-and-pin insulators 11.4 in. in diameter and 5.9 in. pitch. In other words, for unshielded strings the pitch should not be more than about half the diameter of the unit.

2. Shielding. All strings (except perhaps those below 15 in. long) should be shielded. With vertical strings the conductor may provide sufficient shielding if the pitch and therefore the variation in stress on individual units, is not too great; though to be certain that the flashovers clear the string, arcing-rings should be used.[5] In other positions the conductor may not provide sufficient shielding; then ring shields must be fitted.

3. The Flashover Voltage-Distance Relation is not straight line, but lies between the point-to-point and point-to-ground-plane curves.

4. The Lowest Flashovers are obtained with strain strings. But these values are not below the point-to-grounded-plane arc-overs for the same distances.

5. Length of Strain Strings. These need not be more than five per cent longer than suspension strings; that is, one unit in twenty should be added to the normal vertical string to guard against the capacity effect of the strain towers. Additional units may also be necessary to overcome special local atmospheric or dirt conditions.

6. Double Strings have the same flashover as single strings of the same length, if both are adequately shielded.

7. Calibration of Voltmeter. Voltmeter-coil (or potential-transformer) readings should be calibrated by some suitable method for each particular type of set-up.

ACKNOWLEDGMENTS

The author is deeply indebted to Dr. H. J. Ryan for his helpful criticisms and to Professor J. S. Carroll and the other members of the laboratory staff whose experience and assistance, both mental and physical, were invaluable.

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Discussion

Bradley Cozzens: It has been pointed out that the condition for the maximum field intensity on a point having a definite distance clearance, is to place that point at the center of a sphere. It is practically impossible to have the point at the center of a hemisphere. The point-to-plane condition approaches this latter setup, and is the practical condition that gives the lowest

Fig. 1

arc-over voltage for a given distance between electrodes. The value of point-to-plane arc-over voltage is thus the safe value to use in that portion of tower design which is based on flashover distance. The results of Mr. Angus show that the insulator string flashover values approach the point-to-plane arc-over voltage as a minimum.

Mr. Angus states that double strings have the same value of flashover voltage as do single strings of the same length. It has been the practise in past years to use the double string in prac-

tically every place where especially high strength is necessary. These have been replaced in some cases by the new high-strength units, but there are still many places where the double string is used. The wet arc-over of an insulator string is quite different from the dry condition which Mr. Angus has considered.

The voltage distribution on a wet insulator string is anything but uniform. Taking a double string that is wet, the voltage may pile up on the two or three line units of one of the strings; so that the remaining portion of the string is practically entirely at ground potential. On the other string of the pair the high-voltage stress may be on the tower end of the string. This means that the entire string with the exception of the two or three units at the tower end of the string will be at line potential. The fourth unit in this string will be at line potential, while the fourth unit in the paralleling string is at ground potential. This high potential difference between the two strings is in many cases sufficient to break down the air between the two strings, and result in a complete arc-over of the string.

It has been found in practise that double suspension strings do have a higher rate of failure in dust and fog conditions than do the single suspension strings.

Mr. Angus has given some valuable information in this paper in regard to the two conditions which he has investigated. There are, undoubtedly, many other conditions which might be considered, but it is of the utmost importance to the man who is designing towers to have definite values upon which to base judgment in regard to the value of pitch as affecting the string flashover.

P. H. McAuley: (communicated after adjournment) Mr. Angus has studied the 60-cycle flashover characteristics of suspension insulators of two different pitches or spacings. The longer spaced units showed a greater tendency to cascade. It is inferred that cascading flashovers will not occur if the pitch of the insulators is sufficiently small. These conclusions seem perfectly valid in so far as the effect of cascading on the magnitude of the 60-cycle flashover voltage of a given string is concerned.

However, from a service point of view we are interested in cascading because of the liability of damage to the porcelain disks. Apart from foreign conducting material, perhaps most line flashovers are caused by surge voltages. Hence, we are really more interested in the nature of the surge flashover, because it seems reasonable to assume that the power current will follow the arc path established by the surge. Laboratory tests indicate that surge voltages invariably cascade insulator strings that are not protected by arcing rings. Fig. 1 shows a surge flashover of a 12-unit string of suspension insulators of 10-in. diameter disks and 4¾-in. spacing. It is noticed that the arc clings to the porcelain surface of every unit in the string. In our experience this is characteristic of surge voltage flashovers regardless of insulator pitch of spacing.

Impulse Insulation Characteristics of Wood Pole Lines

BY H. L. MELVIN*
Member, A. I. E. E.

Synopsis.—This paper gives the results of a rather comprehensive series of tests on the impulse insulation characteristics of wood and on combinations of insulators and wood as used in wood pole transmission line construction; and suggested methods of protecting wood from damage due to lightning discharges; also a brief discussion on the application of the data.

I. INTRODUCTION

WOOD poles and crossarms have been used in transmission line construction since the beginning of electric power transmission. That wood has insulating value has been recognized through these years both in the field and laboratory and it has been utilized to a greater or less degree either intentionally or accidentally as a part of the insulation for transmission lines on practically every power system. In some localities it has been possible to use treated wood as a part of the normal line voltage insulation but frequently it is not even practicable to have wood in the insulating circuit, between phases at least, on account of the possibility of crossarm and pole burning caused by leakage currents.

With steadily applied voltages the insulating value of wood varies over a very wide range depending upon the treatment, kind of wood, moisture content, and amount of contamination. Ordinary types of line insulation are also affected by moisture and contamination; however, it has been learned that these factors do not influence their impulse insulation characteristics materially. It has also been observed, from analyses of operating performance of transmission lines from a lightning standpoint, that those utilizing some part of the wood apparently have better records than lines with the same amount of porcelain insulation but with the hardware bonded and grounded.

Consideration of these factors made it desirable to undertake a special study of the impulse insulation characteristics of wood for its practical value in the design and operation of wood pole lines, to provide a means of placing some measure of value upon the many schemes being proposed and tried which use wood as insulation, and as a supplement to the rather intensive investigation of the lightning problem being conducted in the field and laboratory. Accordingly a rather comprehensive series of tests was undertaken for the purpose of obtaining some fundamental data on the insulating value of poles, crossarms, and combinations of insulators, crossarms, and poles to impulse voltages, also on methods of protecting wood from damage due to lightning. With these data available it should be possible to use wood in a more intelligent manner in design and better understand the performance of various types of construction where wood constitutes part of the line insulation.

II. TEST IMPULSE WAVE

The impulse voltage wave used for all the tests can be described as one reaching its maximum value in approximately one-fourth of a microsecond and then decreasing to one-half of its maximum in approximately twenty microseconds. The voltages recorded are the minimum crest values required for sparkover on the tail of the wave.

While the sparkover voltage values would vary with the type of impulse wave used, it was not considered practicable to extend the tests to cover other types of voltage waves, particularly since no actual determinations of the character of lightning voltages had been made at that time. These tests should be interpreted as not necessarily representing actual lightning conditions but as giving comparative sparkover voltage values for the particular voltage wave.

Voltages having maximum values of 400 kv. to 3000 kv. were employed. Several shots were required in making each point determination and as would be expected in testing insulation having the characteristics of ordinary wood, the test points were rather erratic. The actual test points have not been shown on the curves in the various figures, but rather they represent averaged results. The dashed curves and portions of curves are interpolations and extensions.

III. IMPULSE SPARKOVER VOLTAGES

General. Sparkover voltage tests were made on cedar, chestnut, and treated pine poles; fir and treated pine crossarms; treated hardwood and pine sticks; and combinations of insulators and crossarms; insulators and poles; and insulators, crossarms, and poles. The poles and crossarms were of dimensions that might be used on a line except that the poles were shorter. The dimensions of the sticks were about those considered suitable for use as long wood guy insulators. The combinations of insulators and wood tested were as might be used in 66 kv. to 132 kv. construction.

To study the influence of moisture, conductivity, and contamination on the impulse sparkover values, one each of the different varieties of poles was kept under

*Engineering Department, Electric Bond & Share Company, New York, N. Y.

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cover for over two weeks so they contained the usual amount of moisture in a dry pole, another set was kept in a similar way but their surfaces were wet before test-

Fig. 1—Impulse Sparkover of Wood Pole

ing as would be the case in a heavy shower, a third group was soaked in a vat of ordinary tap water for about two weeks to thoroughly wet the wood fibers, the

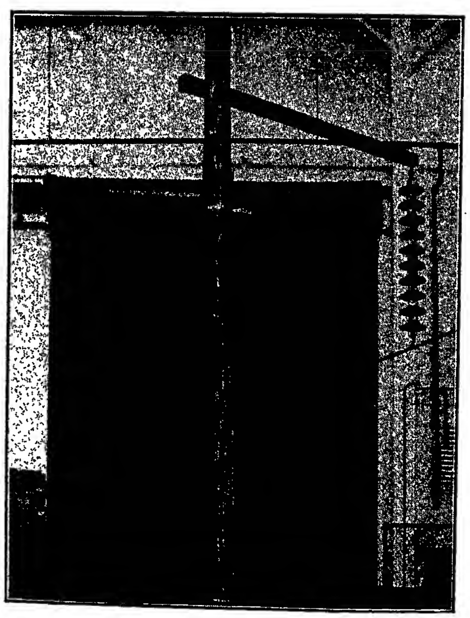

Fig. 2—Typical Test Assembly

fourth soaked in a vat of salty water (about one-fourth as salty as sea water) for about two weeks to increase their conductivity, and to other samples a coating of wet cement was applied to simulate contamination. The crossarms and sticks were prepared in a similar manner, several similar samples being given the same treatment.

Poles, Crossarms, and Sticks. Tests were made on the dry, surface wet, tap water soaked, salt water soaked, and cement coated poles in varying lengths from 4 ft. to 14 ft. The results indicated that the impulse sparkover values are not materially affected by the variety of wood, treatment, moisture content, contamination, or salt water absorption. The salt water soaked cedar

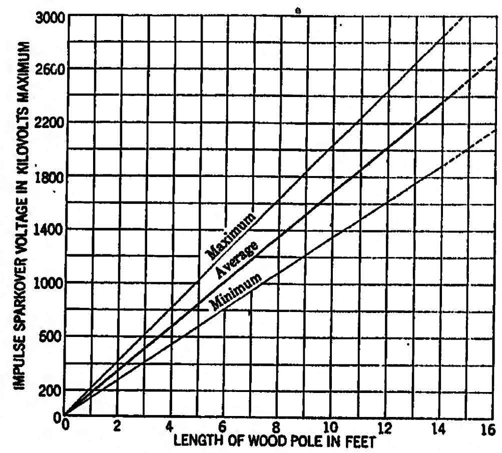

Fig. 3—Sparkover Voltage of Wood Poles

pole, however, did give values lower than any of the others, probably on account of its very low conductivity, but since it did not represent any probable field condition, it was not included in the results. Many values obtained from the wet and salt water soaked samples

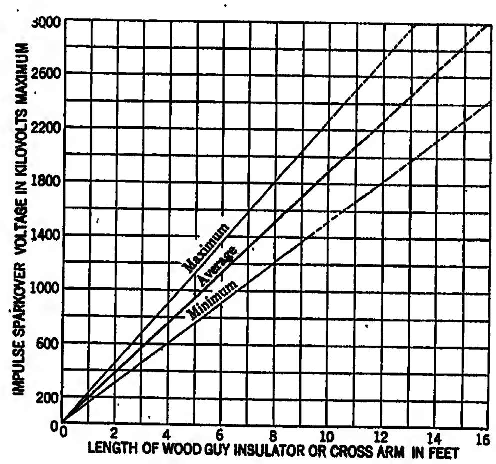

Fig. 4—Sparkover Voltage of Wood Guy Insulators and Wood Crossarms

were higher than those from corresponding dry samples. Adding a 200-ohm resistance in series with a pole, simulating high ground resistance, did not measurably affect the sparkover value.

Fig. 3 gives the results of the tests on poles. The test points fall between the maximum and minimum curves which vary about 20 per cent above and below

the average value of approximately 170 kv. per ft.

Similar results were obtained from tests of crossarms and wood guy insulator sticks, little difference being found as between hardwood, fir, or pine and the treatment or moisture content. A slightly higher insulating value than that obtained for poles was indicated, however, probably due to their smaller cross-section and the better class of wood. The results are shown by the curves in Fig. 4.

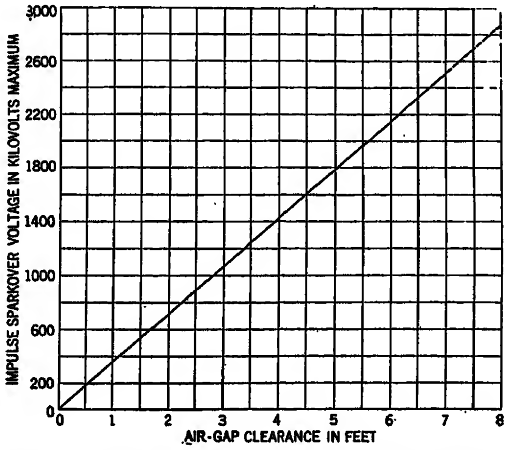

Fig. 5—Sparkover Voltage of Air-Gaps

Air-Gaps. Sparkover voltage measurements were made for air-gaps such as obtain between conductors and guys or grounded parts of structures and across horn-gaps. These gaps are somewhat similar to needle-gaps but usually, on account of the hardware and configurations involved, should have slightly higher sparkover values than needle-gaps. It is believed the test set up was fairly representative of actual conditions and the resulting values are given by the curve in Fig. 5.

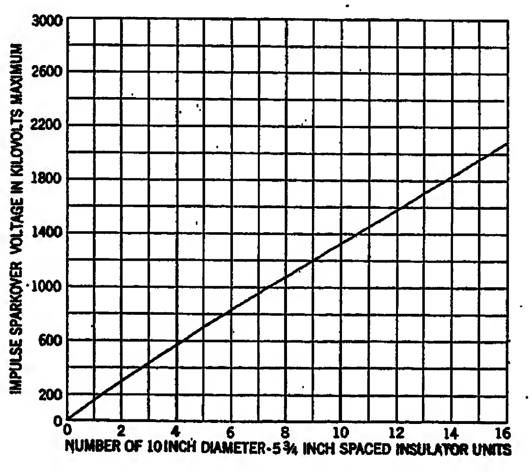

Fig. 6—Sparkover Voltage of Suspension Insulators

Insulators. Fig. 6 gives the sparkover voltages for 10-in. diameter 5¾-in. spaced suspension units of the ordinary design for the 20-microsecond wave, as taken from the recent paper on *Lightning* by F. W. Peek, Jr.* All tests were made with this type of unit with the exception of those using a 70-kv. pin type insulator of usual design.

Combinations of Insulators, Crossarms, and Poles.

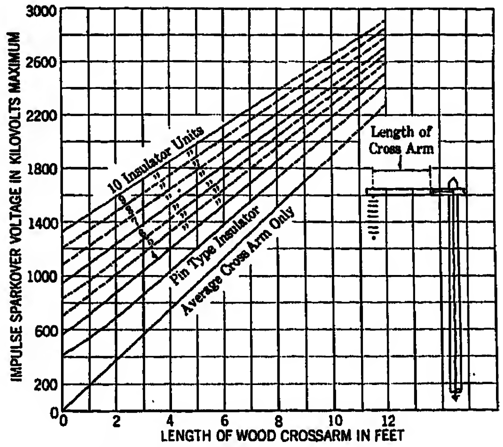

Fig. 7—Sparkover Voltage of Insulators and Wood Crossarm

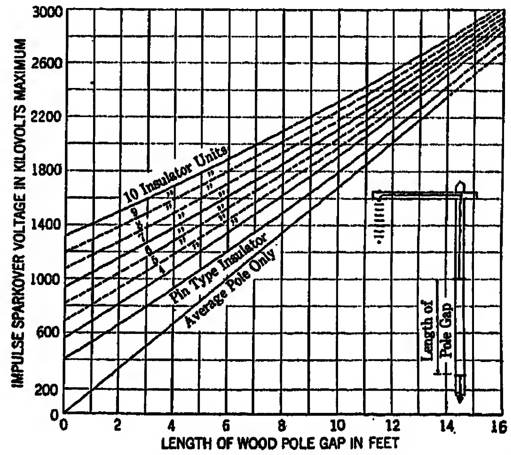

Fig. 8—Sparkover Voltage of Insulators and Wood Pole

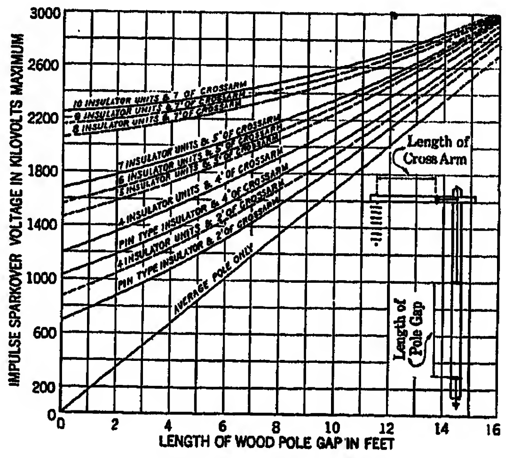

Fig. 9—Sparkover Voltage of Insulators, Wood Cross-Arm, and Wood Pole

Figs. 7, 8, and 9 give the average sparkover voltages for combinations of insulators and varying length of crossarm, insulators, and varying length of pole and different combinations of insulators and cross-

*See Bibliography for references.

arms with varying length of pole respectively. The suspension units were hung from the crossarm by means of an ordinary eye bolt as illustrated by Fig. 2, and the pin type insulator was mounted on a 13-in. pin. The crossarms and poles were tap water soaked and had approximately average insulation characteristics; however, all curves were adjusted to represent an average of the samples.

The sparkover voltage values of the component parts cannot be added directly as will be noted, on account of the differences in the characteristics of porcelain and wood insulation and their physical relations in the ordinary transmission structure.

If sparkover values are desired for combinations different than those shown or for suspension insulators with spacings other than 5¾ in., values can be interpolated by shifting the starting point of the curves or making estimates from the combinations covered by the tests. For example, eight 5-in. spaced units have approximately the same impulse sparkover as seven 5¾-in. spaced units so the seven unit curves may be used for estimating the sparkover voltages with eight short spaced units in the various combinations.

Partial Sparkover of Combinations of Insulators, Crossarms, and Poles. Sparkover of the insulators only may occur with impulse voltages applied to combinations of insulators and crossarms, insulators and poles, or insulators, crossarms, and poles, at lower values than are required to completely spark over the combinations.

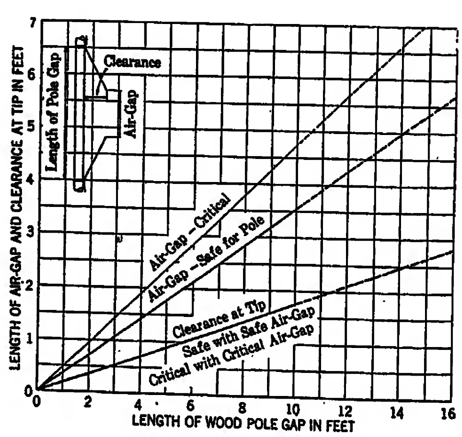

FIG. 10—HORN-GAP PROTECTION OF WOOD POLES

The voltages at which these partial sparkovers occurred seemed to be primarily a function of the moisture content or conductivity of the pole or crossarm. With a dry or wet crossarm or a dry pole in series with the insulators, the voltages at which partial sparkover occurred were about the same as required for complete sparkover of the assembly. However, with a soaking wet pole the voltages at which partial sparkover occurred approached the sparkover value of the insulators or insulators and crossarm only. The intensity of the partial sparkover arc was very much lower than that for normal discharge of the lightning generator.

The results of these tests are not included in curve form as they were very erratic, depending upon the condition of the poles; also direct practical application could not be made of the data. They did, however, indicate possible limitations in the effective use of poles to increase the insulation of all three power conductors from ground. For example, should simultaneous partial sparkovers occur on two or more phases on the same structure followed by dynamic current, a phase-to-phase flashover might occur at lower lightning voltages than would be required to cause a flashover to ground. Operating experience and possibly additional tests

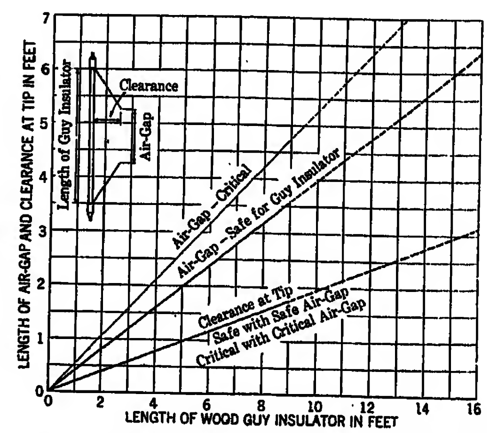

FIG. 11—HORN-GAP PROTECTION OF WOOD-GUY INSULATORS

having available 60-cycle dynamic voltage on which the impulse wave is superimposed will be required before the possible effect of partial sparkovers on line operation can be estimated.

IV. PROTECTION OF WOOD FROM DAMAGE

Wood poles and crossarms are frequently damaged by lightning discharges and it is therefore essential that some means be devised for protecting wood from such damage if it is to be used as part of line insulation to lightning voltages.

A simple device used in the tests consisted of protecting horn-gaps so proportioned that the impulse discharges occurred across the air-gap rather than along the wood. It was also indicated that, whenever the sparkover value of the parallel path was lower than that of the wood being protected, all discharges occurred across the weaker path. Since the sparkover voltage values for wood were found to vary it is necessary that the gap be so designed to afford protection even though the particular wood specimen might have lower than average insulation strength.

Figs. 10 and 11 give the controlling dimensions for designing horn-gap protection for wood poles and guy insulator sticks respectively. Dimensions taken from the "safe" curves should protect poles and sticks having insulation strengths corresponding to the low samples tested and the margin between the "critical" curves and "safe" curves indicates the factor of safety under average conditions. Not only must the air-gap

be of the proper relative length but the clearances from all points of the horns to the wood must be such that arcs will not occur from the horn to the wood and then along the surface of the latter.

Another method of protecting guy insulators from damage in the event of structure flashover is by means of a parallel gap, having a lower sparkover value than the insulator, installed on the pole. Fig.12 illustrates this scheme and gives the relation between pole-gap and guy insulator lengths. To provide for the possibility of a high insulation strength pole being combined with a low insulation strength guy insulator it is necessary to allow a differential as shown by the "safe" curve. Damage will, of course, occur in this pole-gap in the event of flashover unless it is protected. If protecting horns are to be installed, the critical curve should be used in determining the pole-gap and the protecting horn-gap dimensions should then be proportioned as shown by Fig. 10, otherwise by using the "safe" pole-gap curve and the "safe" air-gap curve a double factor or safety would be provided.

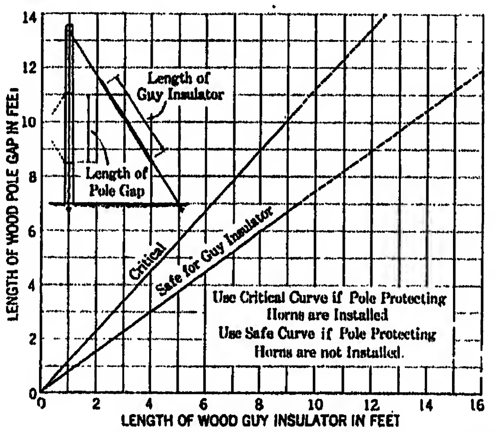

FIG. 12—RATIO OF WOOD-POLE GAP TO WOOD-GUY INSULATOR FOR GUY INSULATOR PROTECTION

To determine whether an ordinary differential in ground resistance between pole and guy would make such a protective scheme unstable, a 50-ohm resistance was inserted in series with the pole-gap and this amount of resistance did not affect the relations.

Protecting gaps for crossarms must be designed for each combination of insulators and crossarm length as the voltage appearing on the crossarm is dependent upon the relations in the particular combination and the protecting air-gap must be so proportioned that it will have a sparkover value lower than the voltage appearing on the crossarm. Actual tests were not made to determine controlling dimensions for crossarm protecting horns; however, a suggested procedure is as follows, from Fig. 7 obtain the sparkover voltage of the particular insulator and crossarm combination, interpolating if necessary, then determine the increase in sparkover voltage effected by the crossarm by subtracting the sparkover voltage of the insulators alone, take 80 per cent of the resulting value to allow for variations in crossarms, determine the air-gap length from Fig. 5, and then obtain the clearance between the horn tip and crossarm directly from Fig. 11, using the clear length of crossarm to be protected as the abscissa.

The use of two or more shorter gaps in series might seem preferable and this scheme was also experimented with, but the sparkover value of gaps in series is rather indefinite unless all gaps are identical. The single gap would also seem less objectionable and more practicable of application even up to dimensions for protecting wood pole gaps longer than 20 ft. Whether protecting horns for poles, wood guy insulators, and crossarms designed with these dimensions will be effective for actual lightning must be demonstrated by field application, or when more is learned about lightning, including direct strokes, it may be possible to more nearly simulate the conditions in the laboratory and devise improved methods for protecting wood or modify the dimensions given by the curves.

V. APPLICATION OF DATA

General. This investigation and discussion should not be interpreted as a recommendation for the general utilization of wood to increase the impulse insulation strength of lines. It is not always practicable to use wood in this manner on account of the possibility of crossarm and pole fires. The values of increased impulse insulation as reflected in the improved performance of transmission lines has not been definitely established. Furthermore, in some cases it may not be effective or advisable to increase the impulse insulation strength of lines materially above that of the substations and terminal apparatus.

In sections of the country where lightning is regarded as severe, several lines have been constructed and existing lines modified using wood in the various ways decribed below, from which some actual operating experience should soon be available. It must be remembered, however, that considerable time may be required to obtain authentic and conclusive confirming results from operating experience, since lightning storms must occur at the particular installations and careful analyses be made of what actually occurred from the evidence left by the storms.

The surge voltage investigations conducted during the past few years, which have included some lines using wood to a limited degree and one section of line in particular using long wood guy insulators have, however, yielded a few lightning voltage records of the order indicated by these tests. The plan for protecting long wood guy insulators by means of a parallel gap on the pole, as illustrated by Fig. 12, also seems to be effective from the limited operating data now available.

Present Conventional Designs. An analysis of the insulation strength of conventional wood structures in existing lines, using the wood to some extent as insulation, will no doubt reveal inconsistencies which might readily be corrected. Clearances between conductors and guys or other grounded parts of structures and the

amount of insulation wherever the insulator hardware is grounded should be checked in particular. It may also be practicable and should be very desirable to make the impulse insulation strength of all structures in a line uniform or at least design them for a uniform minimum value. Damage to wood from lightning may be reduced in particular cases if simple protecting horn-gaps can be applied to the affected parts of the structures.

The data can also be used to compare the relative impulse insulation strengths of different lines, also the insulation strengths of lines with that of terminal substations and apparatus.

Modified Designs. Where practicable to use wood as part of the line impulse insulation, the crossarms and poles can be employed in varying degrees in combination with the insulators. In designs of lines with conventional overhead ground wires and those with pole ground wires, installed for protecting poles from damage, the crossarms can frequently be used to increase the insulation strength. Attention must, of course, be given to those structures where the insulator hardware is grounded to provide the additional porcelain necessary to make them the equivalent of the other structures in the line. Whether crossarm protecting horns should be used or not would depend upon the particular combination of insulators and crossarm as well as past experience in the territory with similar construction.

It was observed during the tests that with four or more suspension units or a 70-kv. pin type insulator and about two feet of crossarm, the arc would usually strike to the ground connection clear of the arm, but with longer lengths of crossarm the arc usually cascaded the insulators and arm. Actual lightning may not perform in the same manner but it has been observed that relatively little damage is done to short crossarms or arms with crossarm braces which short circuit all but about two feet of their length. On the other hand, long crossarms are frequently damaged.

The impulse insulation strength of the conductors to ground, on lines not employing overhead ground wires, can be materially increased by utilizing the crossarms and a considerable portion of the poles. Long wood guy insulators are required in such designs to increase the insulation of the guyed structures. If bonding of the insulator hardware is necessary on account of burning due to leakage currents, the poles only can be used, increasing the insulation of the three conductors as a group to ground. There are several factors to be taken to account in preparing these designs, particularly at angle, dead end, and special structures and for lines having communication or distribution circuits on the same poles, which cannot be properly treated in this paper.

An example of a rather favored experimental design for H frame 66-kv. to 132-kv. lines, employs wood guy insulators about 20 ft. long, (usually two 10-ft. insulators in series); the end sections of the crossarm are either bonded to the top section of the pole grounding wire or crossarm protecting gaps are installed on the end sections; no bonding wire is placed along the crossarm between the poles increasing the phase-to-phase insulation, also there is little probability of severe damage in this section of the crossarm; pole gaps with protecting horns are installed at the guyed structures to protect the guy insulators and poles; the unguyed structures may not have any bonding or pole ground wires installed in order to obtain the maximum possible insulation, or unprotected gaps may be cut in the pole grounding wires such that their insulation strength will be equivalent to the guyed structures; or in severe lightning territory protecting horns may be used on all pole-gaps. The lower ends of the guy insulators and pole-gaps are kept about 10 ft. from the ground. Such designs will have from 2500-kv. to 3000-kv. impulse insulation strength to ground based on the results of these tests.

A line immune from lightning flashover cannot be built in this fashion as the small amount of operating experience already available has demonstrated. Experience has also shown that structures without the insulator hardware bonded or grounded frequently flash over and are damaged. If present reasoning is correct, however, it should require a direct stroke to the line or structures or an induced stroke of approaching maximum value to cause flashovers on lines with insulation strengths of the above order.

To be immune to lightning a line must either be capable of receiving a direct or branch stroke terminating on conductors or structures, with some means provided for relief of the lightning energy without dynamic follow up, or direct strokes must be effectively diverted from the line and the line insulation be such that flashover will not occur due to the voltages which can appear on the line conductors when lightning discharges occur to the diverting structures.

A general design along these lines might consist of a wood tower line constructed about as described above, using long wood guy insulators, with direct stroke protecting wire or wires erected over, or over and to one side, or possibly on both sides of the line, at a height such that direct strokes will occur to the protecting wire or wires rather than to the line conductors or structures. The protecting wire or wires might be grounded at two or more points in each span to reduce the impedance voltage drops to earth. Sufficient insulation through the air paths between the direct stroke protecting wires and the line conductors would of course be necessary, so that side flashing would not occur to the line. The impulse insulation strength of the line or combination of insulation with conventional overhead ground wires must be such that insulation sparkover will not occur for the induced voltages appearing on the line conductors. Instead of the overhead direct stroke protecting wire or wires, tall masts might be substituted so arranged as to divert direct strokes from the

line. Experimental applications of schemes of this kind are expensive; considerable time might be required to demonstrate their merit conclusively, and at the present time there is hardly sufficient information available for the preparation of designs, which would offer promise of functioning, without providing unreasonable factors of safety and at undue expense.

How important a part the use of wood may play in the insulation of lines for lightning voltages in future designs cannot be predicted, but it would seem probable that it may be used quite extensively in experimental installations and in connection with field research and lightning investigations.

Substation Protection. When transmission line impulse insulation strengths are increased above what is now regarded as normal for lines or for substations and terminal apparatus, as would seem possible if wood is utilized to any appreciable degree, attention must be given to substation protection from surges originating on the lines. Spillway or protective gaps set at substation insulation levels or slightly lower, or reduced insulation adjacent to substations, lightning arresters, or combinations of the above should provide the desired protection. Furthermore, lightning voltages seem to attenuate very rapidly in traveling along transmission lines so high impulse insulation should usually be effective over the major portion of lines between substations and the protective devices should only be called upon to function for some of the surges originating relatively near the terminal equipment.

CONCLUSIONS

Wood seems to have quite definite impulse insulation strength which is fairly uniform, within practical limits, for the different varieties of wood used in transmission line construction; also it is not materially affected by moisture or contamination.

It should seem practicable to utilize wood to increase the impulse insulation strength of lines in many situations and these test data should be an aid in designing the structures so they will each have the desired uniform minimum insulation strength.

The impulse sparkover voltages of combinations of insulators and wood are not equal to the sum of the sparkover values of the component parts on account of their physical arrangement and the differences in their characteristics.

Partial sparkovers may occur, where poles and crossarms are used as part of the impulse insulation, particularly when the wood is wet, at lower lightning voltages than are required for complete sparkover to ground, possibly resulting in phase-to-phase flashovers.

The normal amounts of porcelain insulation required to successfully insulate normal line voltages cannot be reduced by utilizing wood on account of the probability of crossarm and pole fires; also, wet wood has very low insulating strength to steadily applied voltage.

Wood can evidently be protected from damage due to lightning discharges by providing a parallel air-gap of lower sparkover voltage value than the section of wood being protected.

Any application of these data should be regarded as experimental until such time as they have been demonstrated as applicable to actual lightning conditions. A definite statement cannot be made at this time regarding the value of increased impulse insulation as measured by improved line performance.

The voltage values given by the curves are for the particular impulse wave used in the tests and represent average values for the given test conditions.

These tests, while quite comprehensive, should not be considered as complete. Further tests would be very desirable, particularly if the impulse wave were superimposed upon normal 60-cycle voltage so that the effects of partial sparkovers could be studied as well as the behavior of 60-cycle voltages in following up long impulse arcs. Tests utilizing impulse waves of varying types would also yield valuable data and possibly the studies should be extended to cover these when more definite data are obtained on the characteristics of actual lightning and switching surges.

ACKNOWLEDGMENTS

The tests which form the basis of this paper were conducted in the High-Voltage Laboratory of the General Electric Company under the direction of the engineering department of the Electric Bond & Share Company for the Carolina Power & Light, Florida Power & Light, and Texas Power & Light Companies.

Mr. A. E. Silver, Mr. C. A. Jordan, and Mr. L. B. Cowgill of the Electric Bond & Share Company participated in the planning of the tests and preparation of the paper. Mr. Cowgill also assisted at the laboratory and in the analysis of the data.

The co-operation of the General Electric Company and valuable suggestions from Mr. F. W. Peek, Jr. in planning and arranging the tests as well as the assistance of Mr. W. L. Lloyd, Jr. in conducting the laboratory work are very much appreciated.

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Discussion

L. R. Gamble: Following up the tests recently made in Pittsfield on the insulating value of wood poles, the Washington Water Power Company has incorporated a few of the ideas that seem to be reasonable in the use of wood insulation for protection against lightning impulses, and has redesigned its 110-kv. wood-pole structures to take advantage of wood insulation. We did not use wood guy insulators, but moved all guys to a position on the pole to give greater clearance to conductor and introduce a

section of wood-pole insulation in every instance, the guy where the strain really should be put, but in no case is it sufficiently far away from that point to weaken the construction.

We used cross-arm braces to stiffen our two-pole structures against the prevailing winds in the eastern part of Washington. If we do not use the brace the structures will take a leaning position. Nevertheless, when it was found the brace was depriving us of two feet of insulation in the cross-arm itself, we decided to omit the brace.

Our older lines were insulated with six disks, which gave us about 900-kv. impulse breakdown with the cross-arm braces used, and with 30-in. clearance to guys. By removing the braces and increasing clearance to guys to 4 ft. 6 in. we get about 1600-kv. To have obtained this by additional insulators would have meant the addition of two more disks in each string.

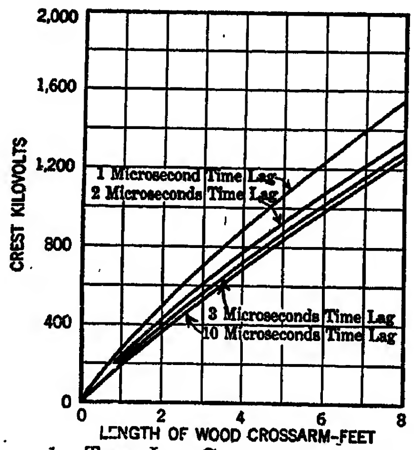

FIG. 1—TIME LAG CURVES OF CROSSARM

A wood brace from the cross-arm to the pole could have been used, but it was felt this expense was not justified.

To make the line symmetrical throughout in regard to the impulse insulation of 1600-kv. would have required eleven disks in every string on angle structures. To obviate this the guying of angle structures was arranged to get the equivalent insulation in the pole itself.

The tests as covered in Mr. Melvin's paper indicate that each foot of wood insulation is equivalent to one disk of insulation on the conductor.

F. D. Fielder: Tests on wood insulation have been made at the Westinghouse High Voltage Laboratory with an approximately flat-topped wave; it is believed that a comparison of some of these results will show the relative variation obtained with different impulse waves.

The wave used at Trafford rises to its crest in approximately ¾ microsecond and decreases to half of this value in 50 microseconds. It is practically a flat-topped wave to the breakdown point in most tests. By varying the crest value of this wave it is possible to obtain a wide range of breakdown voltages at different time lags. Such a process provides data which completely show the characteristics of the insulation under test. Cathode ray oscillograms of each test furnish a means of accurate measurement and analysis.

Two series of curves which are directly comparable with Fig. 7 of the paper are shown. The first set, Fig. 1 herewith, presents a series of time lag curves obtained on a 5 in. by 5 in. dry oak cross-arm, and shows voltage crest measurements corresponding to 1, 2, 3, and 10 microsecond time lags. The second set, Fig. 2 shows similar data obtained with five standard suspension insulators suspended from the end of a horizontal cross-arm. Thus a considerable variation in flashover voltage is shown for identical conditions. Similarly, tests have shown that 16 standard suspension units will flashover in 10 microseconds on impulse waves with a crest value as low as 1450 kv. Also, a 5-ft. needle gap in air will break down on surge voltages of 1000 kv. in approximately 20 microseconds. Actually, the surge breakdown voltage for any piece of insulation is represented by a time lag curve and not by a single value, and it is necessary to study the effect of different voltage waves to obtain complete information. It is hoped that the above comparative results will indicate the order of the variation which may be expected with different waves.

H. L. Melvin: From these tests it would seem that the impulse insulation strength of conventional wood-pole lines, where it is not necessary to bond the insulator hardware to prevent cross-arm burning, could frequently be increased 50 per cent or more by consistent use of a part of the wood in the structures and providing adequate clearances to guys and grounded parts. On lines not employing overhead ground wires, the insulation strength can be materially increased by the use of long wood guy insulators. The relative decrease in the number of transmission-line interruptions which may be experienced with increased insulation cannot be stated. It is very difficult to obtain authentic data of this kind from actual operating experience as lines of different impulse insulation strengths must be available which are subjected to the same lightning influence and comparisons should be made for several seasons. Even when parallel lines are compared, the prevailing direction of storm travel may influence their relative performance.

The results of these tests have been applied experimentally in the construction of a number of lines from which one to two seasons operating experience has been obtained. From these it

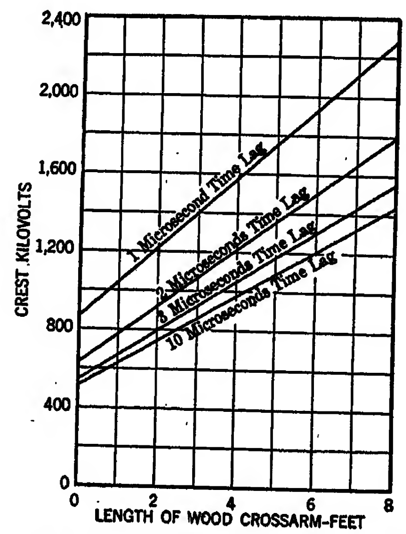

FIG. 2—TIME LAG CURVE OF CROSS-ARM AND FIVE STANDARD UNITS

has been learned, that lines with insulation built up as high as 3000 kv. based on the test voltage wave, are by no means immune to lightning flashover. The scheme of protecting the wood guy insulators by means of the shorter parallel path on the pole, as illustrated by Fig. 12 in the paper, has been fairly successful though in a number of cases the wood guy insulators have been damaged. Numerous discharges across the unprotected pole gaps have been experienced and in several instances the poles have been severely damaged. The by-pass protecting horn gaps using the dimensions given, have evidently functioned to protect the wood though the operating experience covering this feature is at present quite limited.

The discussion and data given by Mr. Fielder are very interesting and illustrate the variation in voltage values which may be

expected by varying the duration of application of the crest value of the impulse voltage. It will be noted that the tail-of-wave spark-over values, obtained with the test wave used in the paper, give values approximating those for a one-microsecond to a two-microsecond time lag and the more nearly flat-topped impulse wave. The variation in impulse insulation strength of the wood specimen with varying time lags corresponds fairly well with the variation in the insulation strength of insulators, so it would seem that the curves in the paper can be used in estimating the relative impulse insulation strengths of insulators, air-gaps, and combinations of insulators and wood, even though the type of impulse wave be varied over quite a wide range.

This assumption is probably sufficiently accurate for practical purposes as the insulation strength of wood is not uniform, also extreme precision in the impulse insulation design of wood-pole lines does not seem warranted. Lightning voltages having equivalent durations considerably over 10 microseconds may be experienced and it is also possible with the longer durations that moisture, contamination, and the resistance of the wood may influence the sparkover voltage values to a greater extent than with the laboratory test wave employed. The actual voltage values do not mean a great deal except for making comparisons and in so far as they may be correlated with actual lightning voltage values.

The Theory of Electrical Conductivity
Recent Developments

BY WILLIAM V. HOUSTON*
Non-member

Synopsis.—This paper explains the electrical conductivity of metals in light of recent discoveries regarding the behavior of electrons. It is claimed that these discoveries have made possible a satisfactory theory of conduction. The more important discovery is that of the wave nature of the electrons. The other new discovery is known as Pauli's "exclusion principle" which states that no two electrons in a wire can have exactly the same velocity and direction of motion. In working out the theory, the statistical method of the Fermi distribution function is employed.

The paper shows that the theory satisfactorily explains how there may be emissions of electrons from a hot wire in spite of the fact that very little energy is put into the electrons by raising the temperature; it explains relative resistances of metals and their alloys, the contact potential between metals, the thermoelectric effect, the Peltier effect, and the change in resistance due to a magnetic field.

* * * * *

FOR the past 30 or 40 years the attempt has been made in the study of physics to explain all of the properties of matter on the basis of ultimate electrical particles. It has been assumed that a piece of material is made up of a very large number of positively charged particles called protons, and of negatively charged particles called electrons. This assumption is based on the experimental fact that it is possible to separate positive and negative particles from all kinds of matter. The numerical value of the charge on one particle is found to be the same as that on the other. Furthermore, the total numbers of protons and electrons are the same, so that there is no electrical charge on the body; but the mass of a proton is some 1840 times as large as that of an electron, so that the weight of a body is essentially that of the protons. It is found that all of the protons and about half of the electrons are gathered together into small clusters which are the atomic nuclei. These nuclei then have a resultant positive charge, and are surrounded by enough negative electrons to make a neutral atom. The number of positive charges on the nucleus, which is the same as the number of electrons around the nucleus, is equal to the atomic number of the element and determines its position in the periodic system of the elements. This method of interpreting experimental facts has had such tremendous success in so many fields that it seems almost certain that, in its broad outline, it represents correctly the constitution of matter.

With this picture, it is relatively easy to account qualitatively for the electrical conductivity of metals. When the atoms are packed as closely together as they are in a metal, the outer and more loosely attached electrons come under the influence of more than one atom and become free. In other words, they cannot be identified as belonging to one atom or another, and they move about between the atoms with very little restraint. Under these conditions, the application of e. m. f. causes these electrons to filter between the fixed atoms, and so, to constitute a current. On the other hand, an insulator is a substance in which all of the electrons are tightly bound to individual atoms.

This idea was given a quantitative treatment by Drude,[1] Lorentz,[2] and others. They started out by treating the free electrons as though they were alone in the metal and behaved exactly as gas molecules, moving about with energy due to temperature. Thus we come to speak of the group of free electrons as an electron gas. If an e. m. f. is applied to such an electron gas, it starts of course an average motion of all the electrons in one direction. If there were nothing to interfere with the motion, the electrons would move faster and faster, and the current would continue to increase without limit. The limit is set, however, by the presence of the atoms themselves, or more strictly speaking, of the positive ions, which form the crystal lattice. When an electron collides with an ion which is more or less tightly bound to its position in the crystal, the electron loses the extra energy which it has acquired from the field. On this account, its velocity cannot increase indefinitely. Thus the collisions of the electrons with the fixed ions are observed as a resistance, and the resistance is proportional to the number of collisions per second.

It is perhaps desirable to look at the relative magnitudes of some of the quantities involved in this picture. If we make the very reasonable assumption that there is one free electron for every atom, there will be about 6×10^{22} free electrons per cu. cm. When there is no e. m. f. applied, these electrons will be moving with fairly high speeds in all directions, but the average velocity will be zero, so that the electron gas as a whole will not move. This distinction between the velocity of a single electron, and the average velocity of all electrons, which latter is the current, is the same as the distinction between the velocity of the molecules of air and the velocity of the air as a whole. The velocity of the molecules we recognize as heat, while the velocity of the whole we call wind. Now the velocity of a single electron will be of the order of 10^8 cm. per sec., while if

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1. For references see Bibliography.

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the average velocity of the whole is as great as only one cm. per sec. there will be the tremendous current of about 8000 amperes per sq. cm. or about 50,000 amperes per sq. in. This shows that the applied e. m. f. produces only a *very minute* change in the velocities of the electrons.

All this, of course, has nothing to do with the propagation of the e. m. f. along the wire. That is governed by Maxwell's equations and can be explained as a result of the mutual repulsions of the electrons. This mutual repulsion can be neglected except, perhaps, in the finer details of the theory of conductivity.

Qualitatively, this picture is very satisfactory; but there are very serious difficulties with the quantitative treatment. In the first place, if there is at least one free electron for each atom in the metal, the electron gas should have a specific heat about half as large as that due to the vibration of the ions which make up the crystal. But the observed specific heat is merely that of the ions themselves. This constitutes a very serious objection to the classical theory, since it indicates that not enough energy is put into the metal when the temperature is raised to account for the assumed increased energy of the electrons. In the second place, the number of free electrons which must be assumed to explain the different electrical properties of a metal varies between such wide limits that the theory is evidently inconsistent. Another difficulty is that when the resistance is calculated by means of this theory it is found to be proportional to the square root of the temperature, which is not at all in accord with the observed facts.

On account of these difficulties, many attempts have been made to give other pictures of the behavior of the electrons in a metal. Some of these have been based on the idea that the electrons do not become free from the atoms, but remain attached and under the influence of an applied e. m. f. occasionally pass from one atom to the next. In this case, of course, the electrons need have no specific heat, since they do not move independently of the atom. But it is just this lack of an independent motion which makes it difficult to explain the emission of electrons from hot wires which we use in thermionic vacuum tubes. It is usually thought that this is due to the fact that certain electrons acquire a very high velocity and so are able to pass through the retaining wall of potential which bounds the metal. If there is no motion due to temperature energy, this could not be the case.

Thus, until recently, the theory of the electrical properties of metals contained a number of conflicting hypotheses, and it seemed impossible to form a consistent theory with a few simple assumptions. Within the last few years, two important discoveries have changed the whole aspect of the situation. Perhaps the more important of these discoveries has been the discovery of *the wave nature of the electrons*.

For several centuries there have been two rival explanations of the phenomena of light,—the wave theory and the corpuscular theory. During the nineteenth century, the weight of evidence became almost overwhelmingly in favor of the wave theory, but with the discovery of the photoelectric effect in 1888, it became necessary to use the corpuscular theory, (which has been called the quantum theory), to explain the phenomena of the interaction of light with matter. But although there have been two theories of light, there has been only one theory of the nature of electrons. Since the very early experiments on cathode rays, there has been practically no doubt as to the nature of electrons. They seemed in every way to satisfy the requirements of corpuscles of electricity. No one ever thought of investigating the wave properties of electrons until it was accidentally discovered in 1927 that a stream of electrons produces a diffraction pattern in the same way as a beam of X-rays.[3] Many theoretical considerations had been pointing toward the necessity of treating electrons as waves under some circumstances. Through this experimental confirmation of the theory, *we have now just as good evidence for saying that a stream of electrons is a train of waves as we have for saying the same thing about a beam of light.* The quantum theory, which was so called because it seemed to require that light should be propagated in corpuscles or quanta, has now come to include the requirement that electrons should have the properties of waves. This duality of nature, of both light and electrons, is now a firmly fixed experimental fact. It is one of the discoveries which has made possible a satisfactory theory of electrical conduction.

The other essentially new feature in the present theory is known as Pauli's exclusion principle. Applied to the problem in hand, this states that no two electrons in a wire can be in the same quantum state, *i. e.*, they cannot have exactly the same velocity and direction of motion. At first this seems an outrageous restriction, and yet there is a great deal of experimental evidence in favor of it. It is the basis of the theory of the periodic system of the chemical elements, as well as the very extensive and satisfactory theory of spectra. This principle, combined with the fact of the wave nature of the electrons, makes it necessary to revise the statistics with which we treat the electron gas in a metal.

On account of the large number of electrons with which we have to deal, it is necessary to use the methods of statistical mechanics. There are several different varieties of statistics, each one adapted to dealing with a certain kind of object. It is perhaps easiest to characterize the different types of statistics by giving their distribution functions. These functions give the number of electrons which may be expected to have velocities in a given range.

The classical statistics were developed largely by Maxwell and Boltzmann, and are adapted to the treat-

ment of material particles. The distribution function for these is

$$dn = A\, e^{-mv^2/2kT}\; d\,\xi\, d\,\eta\, d\,\zeta \qquad (1)$$

This means that dn is the number of electrons, on the average, whose velocity components in the x, y, and z directions lie between ξ and $\xi + d\,\xi$, η and $\eta + d\,\eta$, ζ and $\zeta + d\,\zeta$. v is the total velocity, k is the molecular gas constant, m the mass of the electron, and T is the absolute temperature. The curve of this function for two different temperatures is shown in Fig. 1. It is evident from Equation (1), as well as from

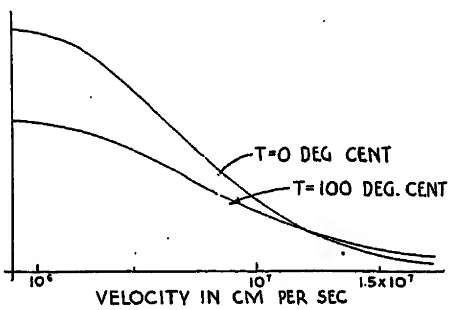

FIG. 1—THE MAXWELL OR CLASSICAL DISTRIBUTION PLOTTED AS A FUNCTION OF VELOCITY

Fig. 1 that as the temperature increases, the curve becomes more and more spread out, so that more electrons are found with high velocities.

The theory of quantum statistics with which we are concerned was developed by the Italian Fermi,[4] and independently by the Englishman Dirac. It is based on assumptions which make it applicable to wave motions when the Pauli exclusion principle applies. Thus, according to our latest knowledge concerning the nature of electrons, it should apply to electrons. The distribution function in this case is

$$dn = \frac{2\,m^3}{h^3}\;\frac{1}{\dfrac{1}{A}\,e^{\,mv^2/2kT} + 1}\; d\,\xi\, d\,\eta\, d\,\zeta \qquad (2)$$

where the letters have the same significance as in Equation (1); h is known as Planck's constant of action and characterizes all equations in the quantum theory. The constant A in both functions is determined so that the integral of dn over all possible values of v gives the total number of electrons present. In the Maxwell distribution function in Equation (1), A is merely a constant by which the exponential function is multiplied, but in the Fermi distribution, the size of A determines the nature of the function. If A is very much smaller than 1, the first term in the denominator is so large that the other may be neglected. The function then becomes the same as the Maxwell function. But in the opposite case, the functions are entirely different. The value of A, when A is large, can be determined from the equation

$$\log A = (h^2/2\,m\,k\,T)\,(3\,n/8\,\pi)^{2/3} \qquad (3)$$

where n is the number of electrons per cu. cm. Because of the very large number of free electrons when it is assumed that there is one per atom, A for ordinary metals is about 10^{90}. Thus, only the case where A is very large need be considered. Fig. 2 shows the curve of the Fermi distribution function for two different temperatures when A is given this value. A gas for which the constant A is greater than unity is called degenerate, and the size of A is a measure of the degeneracy.

It is evident from the curve and from Equation (2) that in the case of the highly degenerate electron gas, the temperature has only a very slight effect on the velocities of most of the electrons. Only the relatively few which have the higher velocities are affected at all. Since the temperature has very little effect upon the motion of the electrons, it follows that the specific heat of the electron gas is very small; in fact it is given by

$$C_v = (\pi^2\,m\,k/h^2)\,(8\,\pi/3\,n)^{2/3}\,R\,T \qquad (4)$$

where R is the gas constant for one gram molecular weight. For room temperature, C_v is less than 1 per cent of the value to be expected with the Maxwell distribution. This is one of the important successes of the present electron theory of metals and was pointed out by Sommerfeld[5] who developed the statistical

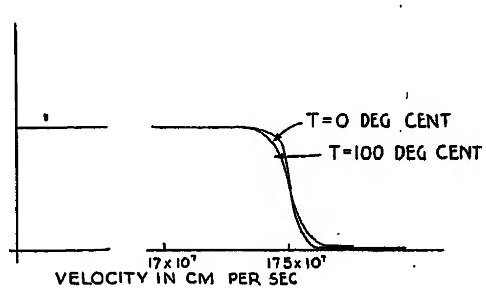

FIG. 2—THE FERMI DISTRIBUTION FUNCTION PLOTTED AS A FUNCTION OF VELOCITY

The scale of this figure is not at all comparable with that of Fig. 1.

phase of the theory. *Now it can be understood why the electron gas makes practically no contribution to the specific heat of the metal.*

But although the free electrons have a very low specific heat, they do not have a low energy of agitation. It is merely that this energy is not given up when the metal is cooled, but is retained and exists at the absolute zero of temperature. The average velocity of a free electron in a metal is of the order of 10^8 cm. per sec. This high velocity and the accompanying energy produces a pressure on the surface of the metal which amounts to something like 2×10^5 atmospheres. Even with this pressure, however, the majority of the electrons are unable to escape from the metal because of the strong electric field which exists at the surface. But there will always be a few with extra large velocities, which can penetrate this surface layer and escape

from the metal, and the number of these increases with the temperature.

In Fig. 3, the Fermi distribution function for the degenerate electron gas is plotted with the energy instead of the velocity, for the horizontal axis. W_i represents the energy at which the function has dropped to ½, while W_a represents the energy which an electron must have to escape from the metal. The electrons which escape are those represented by the part of the curve to the right of W_a. By calculating the number of electrons represented by this part of the curve, and taking account of the various directions in which they are traveling, Sommerfeld has shown that the current per sq. cm. coming from a hot wire is given by

$$I = (4\,\pi\,e\,m/h^3)\,k^2\,T^2\,e^{-(W_a - W_i)/kT} \qquad (5)$$

The equation derived by Dushman and others is:

$$I = B\,T^2\,e^{-b/T} \qquad (6)$$

In Equation (5) $(W_a - W_i)/k$ takes the place of b in Equation (6). This shows that the b which is usually measured and called the work function, is not really the energy necessary for an electron to have in order to escape from the metal, but is the difference between

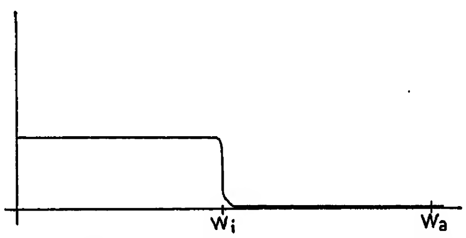

Fig. 3—The Fermi Distribution Function Plotted as a Function of Energy

this energy and an energy which represents the pressure of the electrons inside the metal. In this way, the theory explains completely why we can get emission of electrons from hot wires in spite of the fact that very little energy is put into the electrons by raising the temperature.

The outstanding electrical property of a metal is that of conductivity. It was mentioned above that a current is a relatively slow drift of all the electrons under the influence of an applied e. m. f. This drift would become faster and faster if it were not for the fact that the electrons collide with the metal atoms and so lose the acceleration they have gained from the field. Thus, the average gain in speed and the current is proportional to the time for which an electron can travel without a collision. The average distance which the electron can travel without making a collision is called the mean free path, and this quantity is generally used for calculation instead of the mean time between collisions. Sommerfeld has shown that when the Fermi statistics is used to describe the velocity distribution of the electrons, the specific conductivity in electrostatic units is given by

$$\gamma = (8\,\pi\,e^2/3\,h)\,(3\,n/8\,\pi)^{2/3}\,l \qquad (7)$$

In this equation e is the charge on one electron, h is Planck's constant of action, n is the number of free electrons per cu. cm., and l is the mean free path for those electrons whose energy is equal to the W_i of Equation (6); l is of the order of 5×10^{-6} cm. The mean free path is, of course, a function of the velocity, but only the length of the mean free path at this particular velocity is essential in the conductivity.

In Equation (7) all of the quantities except l are independent of the temperature, and so we must explain the fact that resistance increases with temperature by the fact that l decreases with temperature. It is here that the wave nature of the electron becomes directly apparent. The wavelength of an electron wave is determined by the velocity of the electron through the relation

$$\lambda = h/m\,v \qquad (8)$$

This shows that the faster electrons have the shorter waves. From the Fermi statistics, it can be shown that the free electrons in a metal have such velocities that practically all of the wavelengths are greater than about 5 A or 5×10^{-8} cm. They are longer than most X-rays. This fact is of importance when we study the effect of a crystal upon these waves.[6] The behavior of an electron in a crystal can be considered from two points of view which correspond to the two natures of the electron. From the corpuscular point of view, the electron makes collisions with the atoms in the crystal and so is deflected from its path. From the wave point of view, the electron wave is diffracted by the crystal in the same way that a light wave is diffracted from an optical grating. In the case of electrons in a metal, the wave point of view is the correct one to use. Hence, the problem of determining the resistance of a metal is the same as the problem of determining the scattering of the electron waves by the atoms which form the lattice of the metallic crystal.

It is possible to calculate this scattering effect by the methods used for calculating the diffraction of X-rays by a crystal, when proper allowance is made for the difference in wavelength. The electron waves are longer than the distances between the atoms of most crystals, so that if the atoms were really stationary and regularly arranged, there would be no scattering at ex- and hence, no resistance whatever. This is not the all, planation, however, of the phenomenon of superconductivity, nor of the fact that the resistance becomes zero when the absolute temperature becomes zero, for there is very good evidence that the atoms in a crystal are not stationary, even at the absolute zero of temperature. There are still other ways in which the resistance may become zero, although if there were no motion of the atoms in the lattice, it would certainly be zero.

The thing that produces the diffraction of the electron waves and consequently the resistance is an irregularity in the arrangement of the metallic atoms. This ir-

regularity may come about either through the presence of impurities which distort the arrangement of the atoms, or through the motion due to the temperature energy. This latter effect produces the resistance in pure metals, while the first effect explains why the resistance of an alloy is always greater than the resistance of at least one of its constituents. It is easy to understand from this the reason for Matthiessen's rule which states that a small amount of impurity causes a small added resistance which is independent of temperature. This is explained by the fact that the irregularity in the crystal due to the impurity is essentially independent of temperature.

It is possible to calculate the resistance due to the heat motion of the metal atoms. This kind of calculation shows that the resistance, in its dependence on temperature, may be closely approximated by

$$R \text{ is proportional to } 1/x_0 \int_0^{x_0} \frac{x^4\,dx}{(e^x - 1)\,(x^2 + a\,x_0^2)^2} \quad (9)$$

$x_0 = \theta/T$, where θ is a function of the elastic constants of the metal and T is the absolute temperature; a is a measure of the scattering power of a single atom and so is characteristic of the metal. Equation (9) shows that for ordinary temperatures, the resistance is proportional to the absolute temperature, while for lower temperatures, it falls off more rapidly than would be indicated by the simple proportionality with temperature.

The agreement of Equation (9) with the observations shows that the knowledge of the wave nature of the electron has made it possible *for the first time to give a satisfactory explanation of the way in which the resistance depends on the temperature.*

In addition to the phenomena already mentioned, there are several others which are explained in a satisfactory manner by the present theory. The sudden increase of resistance, which always appears when a pure metal is melted, is due to the destruction of the regularity of the crystal by the metal. The atoms in the solid have a regular arrangement, to a certain extent, while the atoms in the liquid are moving about at random. This loss of regularity causes a large increase in the scattering of the electron waves and a correspondingly large increase of resistance.

The fact that the resistance of a non-cubical metallic crystal is different in different directions can be attributed to the fact that the atoms in the non-cubical crystals can vibrate more easily in one direction than in the others. This causes the diffraction of the electron waves to vary with the direction. The corresponding difference in resistance, calculated on this basis, agrees very well with the observed differences.

A number of other effects, such as the contact potential between different metals, the thermoelectric effect, the Peltier effect, and the change in resistance due to a magnetic field, receive a consistent and satisfactory explanation on the basis of the Fermi statistics and the wave nature of the electron.

The study of atomic structure, which has engaged the attention of physicists for the past 30 years, has now come to the stage where it is possible to treat not only single atoms, but molecules and those very large molecules which we know as solid bodies.

The first extensive application to solids has been the electron theory of metal which has been developed by Sommerfeld, Houston, Frenkel, Nordheim, and Bloch.[7] This brief outline has sought to indicate the degree of success with which the modern theory of the electron has provided a unified treatment of this baffling physical problem.

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Development of Insulating Oils

BY C. E. SKINNER[1]

Fellow, A. I. E. E.

Synopsis.—During the last 35 years or more the development of insulating oil for use in transformers, circuit breakers, etc., has paralleled the development of electrical apparatus. Various steps in the development of oils for this purpose are described in the paper. These include the discoveries from time to time of elements which have been responsible for difficulties which arose in the use of such oils. These include such items as the effect of moisture, the importance of flash and fire test values, the question of fluidity for better cooling, the development of oils with non-sludging characteristics, and a statement of the long series of tests and experiments necessary to eliminate these various difficulties. The importance of a universal oil for insulating purposes is stressed and some of the conflicting characteristics for different uses are described. Attention is called to the selection of the proper raw materials from which insulating oil is derived, together with the extreme care which has been found necessary in the handling of containers, in making shipments, and in applying oil to specific purposes. While much has been accomplished in the securing of satisfactory oil, it is intimated that research and development must be more or less continuous so long as the electrical art advances and oil is used for insulating purposes.

THE integrity of modern transformers and circuit breakers, which are essential features of all transmission systems, is due in no little measure to the insulating oil now universally used in such apparatus. While the oil is a relatively minor part of these devices as a whole, its failure will mean the failure of the apparatus. This is increasingly true as the voltage of the transmission systems is increased. The service rendered by the oil used as an insulating medium in electrical apparatus, is radically different from service rendered by oil in any other class of service and there are rigid requirements for oil for this service which do not exist where oil is used for other purposes. In fact, insulating oil may be considered a material of construction rather than a material of maintenance.

The history of the development of transformer oil begins with the first high-voltage transmission lines in the early '90s, and a continuing and increasing amount of research has been required from that day to this to meet the ever increasing demands for quality and service. The electrical manufacturers' representatives who have been responsible for the quality of the oil used in transformers, have faced many difficulties and have experienced much grief from time to time, due to troubles for which the oil was either directly or indirectly responsible. The fact that such difficulties are rare at the present time does not indicate that further attention to this important material is unnecessary, but on the other hand, it does indicate that a full knowledge of the difficulties which have been so disturbing in the past and a constant watchfulness have mitigated these difficulties to a point where the modern transformer gives perhaps less trouble than any other piece of apparatus in the transmission system.

It may be useful to review some of the history of the development of modern insulating oil and to indicate some of the problems still unsolved, so that a full appreciation by those responsible for the purchase and use of transformer oil may be had. This history may be divided into various chapters, each concerned with the items which seemed to be the cause of the major difficulty prevailing at each particular stage of the development.

When the study was made of oil which might possibly be suitable for the insulating and cooling of the transformers to be used on the Pomona transmission line, this being the first constant high-potential transmission line undertaken in the United States, the study included oils of a very wide variety. Mineral oils, from the heaviest cylinder oil to the equivalent of gasoline and benzine, were carefully studied. Similar tests were made of quite a number of vegetable oils, such as linseed, rosin oil, etc. These early tests were almost entirely on the basis of the determination of dielectric strength. In making these studies, glass containers were used, with the testing electrodes immersed in the oil in a horizontal position. It was observed that any foreign matter visible to the naked eye would line up between the testing electrode and materially reduce the dielectric strength upon the application of the testing voltage, and this at once showed the necessity for extreme care in keeping oil free from foreign matter, such as dirt, fibers, carbonized oil, etc. The necessity for cleanliness has been emphasized again and again with each major increased step in transmission voltages.

In these same tests it was discovered that oil which had been heated in an oven for a considerable period had a much higher dielectric strength than the average oil delivered from the oil manufacturer. There is, of course, the age old tradition that oil and water will not mix, but there seemed no possible explanation for this increased dielectric value of the oil other than that it was due to the elimination of moisture, and that oil was subject to the same difficulties in this regard as most of the other materials of insulation, which at that time had already begun to be studied in considerable detail.

To test the theory, (which from the ancient tradition seemed more or less absurd) that moisture was responsible for the low dielectric value of many oils as delivered, and their changed value on continued heating, the following test was made:

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Extremely small amount of water in increasing quantities was added, each addition being a fraction of a drop per gallon of oil, the oil being very thoroughly agitated after each addition. This gave undoubted evidence that very minute amounts of water in the oil would cause radically decreased dielectric strength. This has been checked again and again during the intervening 35 years and more drastic precautions have been found necessary from time to time as the voltage of transformers has been increased. In fact, it has been found necessary to go to the precaution of treating, not only insulation of the transformer to eliminate moisture, but the whole structure, iron-core frame, etc., and to see that the oil which is introduced, especially in transformers for the higher tension is, as we now say, absolutely dry.

The method of drying oil in the early stages of the transformer oil development was accomplished by giving it an extended heating at moderate temperature; but it was later found that although the temperatures used were relatively low, sufficient oxidation might be started to affect the endurance of the oil against sludging in service. This lead to an investigation of other methods of drying and cleaning the oil, and this is now accomplished by various filtering and centrifuge processes. The requirement is that all suspended matter and all traces of moisture be removed. This is a difficult matter, due to the fact that while the ordinary refining process results in practical elimination of all free water the final moisture to be removed is apparently in solution in the oil.

In the early construction of transformers, the enclosing cases were frequently made of thin material with deep corrugations and with wooden tops, these wooden tops being used for giving added insulation to the outgoing leads. After experience with a number of disastrous fires with constructions of this kind, the underwriters demanded oil having the highest possible flash and fire test, consistent with satisfactory transformer operation. As a result of this requirement, new studies were made and heavier bodied oils adopted. At the same time, attention was given to a better mechanical structure for the transformer cases. The use of this heavier oil resulted in more sluggish circulation and consequently poorer cooling, and apparently little or no decrease in the fire hazard so far as the oil itself was concerned. Soon after this change was made, a new and unexpected phenomenon appeared and this phenomenon is now generally denominated as sludging. This has been perhaps the most difficult matter to deal with that has arisen in connection with transformer oil.

It was soon discovered that a lighter and more fluid oil was in general less subject to sludging than the heavier oils adopted to minimize the fire hazard; but the adoption of these lighter oils merely minimized and did not cure the sludging trouble. As the units became larger and service more difficult, the sludging trouble increased to a point where transformer manufacturers and users found themselves in more or less continual trouble, and very extended studies were made to determine the cause and cure of sludging.

To date, however, no oil has been found which will not deposit sludge if the conditions of its use are sufficiently severe. By very careful selection and by eternal vigilance on the part of the oil refiners and the transformer manufacturers, oil has been produced which under all modern operating conditions is sufficiently free from sludge to give satisfactory service.

Unfortunately, no test has yet been devised which will quickly determine whether or not oil will be free from sludging in service, although an enormous amount of experimental work has been done and many tests have been proposed and used. This question has been considered of sufficient importance to warrant the cooperation of all the nations interested in the production and use of transformer oil to determine, if possible, a satisfactory sludging test. For this purpose, and working through the International Electrotechnical Commission, duplicate samples of oil have been submitted to laboratories of half a dozen or more countries and extensive tests have been entered into for this purpose. At the meeting of the International Electrotechnical Commission in Bellagio, Italy, in October 1927, the report of the various committees and laboratories which have been working on this question for two or three years, was to the effect that the various tests were conflicting in that one test might indicate that a given oil was satisfactory, while another test just as strongly defended, might indicate this oil to be unsatisfactory.

The result of this meeting showed that additional work must be done in order to determine which of the half dozen methods now more or less used would be the satisfactory one to evaluate oil with regard to its sludging characteristics, or whether an entirely new test must be devised. To date, the only safe procedure which has been found has been that of very careful laboratory tests combined with extended service tests, in many cases of several years, to bring the assurance that oil used would show a minimum of sludging troubles.

In the meantime, the oil refiners and transformer manufacturers, and some of the users of transformers, have been making continual studies, both as to the cause and elimination of sludging troubles, and for the securing of oil that would be free from this trouble and would meet all of the other rigid requirements for transformer oil to be used with the highest voltages.

Through a pure accident, discovery was made fairly early in the study of insulating oil to the effect that free sulphur would very greatly impair its insulating value and much study was given at one time to the effect of both free and combined sulphur in minute quantities in insulating oil. In like manner, the residual acids from the refinery treating and other effects of processing the oil, had to be studied with each change in the refining process to bring about the various character-

istics necessary to meet the increasingly exacting requirements on this material.

The manufacturers of apparatus using insulating oils, early found it necessary to establish intimate working relations with the oil refiners and as they were obliged to meet one requirement after another, the refiners developed a special procedure from the selection of crudes in the fields through the final manufacturing process. The characteristics governing selection at the wells include such items as pour point, freedom from wax, amount of sulphur, etc. In some cases special pipe lines are used to transport the crudes selected for the manufacture of insulating oils to the refineries in order that contamination with other crudes shall not occur. During the preparation of the distillate by the vacuum process, rigid inspection for viscosity, flash, and pour point control is maintained and where these oils require treatment with strong sulphuric acid or equivalent, special care is required to see that there is complete neutralization and thorough washing of the oil, and this treatment is sometimes followed by re-distillation in order to remove all traces of reaction products remaining after washing.

The advent of outdoor transformer and switching stations imposed an entirely new requirement on transformer and switch oil, namely, the necessity of a very low congealing temperature, or as commonly known, a low-cold test. Transformer oils which were found relatively satisfactory for the old indoor stations had a relatively high-cold test and consequently were not satisfactory for outdoor stations, particularly in cold climates. This requirement for a low congealing temperature is even more rigid in connection with oil switches, which must be free to operate at any temperature which may be reached in the climate where an outdoor switch may be installed.

This requirement for low-cold test oil demanded a whole new series of studies, as the general requirements for indoor apparatus, such as freedom from dirt, moisture, and relative freedom from sludging, etc., had to be maintained. In all such studies it had to be kept in mind that there was a constantly increasing demand for oil and that any oil selected must be available in sufficient quantity to supply this demand. Fortunately, oil has been developed through the co-operation of the oil refiners and transformer manufacturers, which meets the previous requirements, as well or better than any which had been previously used and which has a sufficiently low-cold test to be satisfactory for all ordinary outdoor service.

From almost the beginning of the development of oil for cooling and insulating apparatus, mainly transformer and circuit breakers, the transformer and circuit breaker requirements seemed to be sufficiently divergent so that no single oil would be satisfactory for both services. Certain characteristics of these two services are in opposition to each other, while certain other desirable characteristics coincide. For example, all the early tests and service experience seemed to indicate that the circuit breaker required a relatively heavy and sluggish oil, while the transformer required as light an oil as possible, in order that it might have sufficient fluidity under all conditions to circulate rapidly and transfer the heat from the transformer windings and core to the outer cooling surface. Again, an enormous amount of experimental work was necessary to find an oil which would meet both these services sufficiently well so that utilities would not be required to carry two or three grades of transformer oil and one or more grades of circuit breaker oil. Several years of laboratory and field tests were carried on before there was sufficient confidence on the part of the electrical manufacturers to justify their making a positive assertion that an oil was available in quantity which had all the necessary requirements sufficiently well fulfilled to justify the stand, that this oil could be used as a universal oil for all insulating and cooling work in transformers and circuit breakers.

It has been found that the balance between the two services is very close, and that continued experimental work and the closest possible inspection and testing of oil of this class must be followed in order that the necessary characteristics may be maintained, suitable for all services and for all climates. The advantages of universal oil are so obvious that no arguments are necessary to justify its use.

Throughout the whole history of the development of oil for insulating purposes the question of shipping containers and storage arrangements has been found to be of the utmost importance. In the early days oil was shipped in wooden barrels which were made tight by the use of ordinary glue. This led to interminable trouble from the glue getting into the transformers and other devices, helping to reduce the dielectric strength and to increase the sludging characteristics. Seepage of the oil and the entrance of moisture were common difficulties with such containers.

With the introduction of steel drums, a new kind of trouble developed. Additional dirt and scale were introduced into the oil and it was soon found that the more rigid cleaning and inspection methods did not always eliminate such difficulties. When the use of oil arrived at a point where tank car shipments were necessary, still further difficulties (dirt and water) appeared. It was not at all uncommon in the early days to find a considerable quantity of water in the bottoms of the tank cars containing transformer oil. Condensation of moisture, both on the exposed surfaces of the tank cars and on the surface of the oil itself, were almost inevitable and imperfectly protected openings frequently resulted in additional trouble.

It had been assumed that steel drums with continuous lead washers under the bungs, would be both proof against seepage and proof against entrance of moisture, but this was found not to be the case, and the writer of these notes is familiar with a considerable

number of cases where drums of oil, with bung-up exposed to the weather, were found to contain a considerable quantity of water, when it was absolutely certain that these drums were moisture free on shipment. This was apparently brought about by the heating and cooling of the oil due to the changes in temperatures, between day and night, the resulting pressure and vacuum helping the entrance of water at the bung when this would be covered by rain water.

The oil refiner has accomplished, therefore, only a part of his necessary functions when he has prepared the proper grades of oil. These must be so handled after preparation as to deliver them in the cleanest possible condition to the ultimate consumer. Amounts of contamination which would be inconsequential in lubricating oils will cause no end of trouble in transformer oils, so that an entirely new scheme of preparation of packages and lines of special containers have been found necessary. Every container returned to the refiner must be most carefully inspected and put in such condition that it will not cause any of this contamination. All rust and any traces of foreign materials which may have been stored in the container and every other kind of contamination must be absolutely removed or the container rejected, and many rejections occur in the inspection of such returned containers. The time between the final cleaning and inspection of containers, and the time of filling with the transformer oil and sealing must be an absolute minimum.

Even with all the possible precautions taken, the practise of making individual inspection of oil in drums after allowing a suitable time for foreign matters to collect at the bottom, has been found essential.

There is involved, of course, the shipment of small packages ranging in volume from one to five gallons. Disastrous experiences were run into through the use of ordinary "run of mill" tin cans in the early stages of the business. It later developed that the cause of this was the use of packages, the seams of which had been soldered with acid flux and the latter material had worked into the cans with harmful results to the dielectric strength of the oil which the packages contained. This has resulted in oil refiners installing a special line of machinery for the manufacture of these containers under such control as to insure against the possibility of their becoming contaminated with materials which cause harm to the oil. Not only must these containers be manufactured properly, but they likewise must be tested for leakage and suitably dried before filling, after which they must be immediately capped with the specially designed fittings which have been brought out for this purpose only. Furthermore, it is necessary that inspection be made of a certain portion of the tin containers in order to insure that the quantity of the oil ready for shipment in these packages is running uniformly satisfactory.

During a few months of the year, under carefully controlled conditions, insulating oils of good dielectric strength could be delivered in ordinary tank cars but because of the extreme difficulty of properly drying them before filling, it is unsafe to guarantee deliveries in these tanks at all seasons. As a result of this condition, special cars have been developed with steam coils surrounding the shell, these coils in turn being protected by wooden jackets covered and protected with heat insulating material and thin sheet iron. Only with such equipment as this has it been found possible to properly dry out the cars before filling to such an extent that delivery of dry oil at destination can be assured. With these cars it is possible to not only dry them out before filling is started but during this operation to maintain the temperature of the cars at such a figure as to assure freedom from contamination of moisture in the oil in the cars before the filling is completed and the cars sealed.

A specific example, involving serious difficulty, will be of interest. Serious operating trouble was experienced with some high-voltage circuit breakers, each containing over 3000 gallons of oil. The oil in this particular case was not the standard usually supplied by the manufacturer. As a result of the difficulty the oil had to be completely replaced in an outdoor installation in severe weather, and in the final investigation the trouble was traced to faulty manufacture of the oil and to sloppy methods in its handling.

It was early seen that some sort of cleaning and drying apparatus was essential in connection with the use of oil in some quantity as is required in the average power transmission station. Various schemes of filtering, drying, and cleaning oil have been devised. These included filtering through paper, unslaked lime, and the application of heat and various other schemes. The plan which seems to give the best all-round results and is now quite generally used, is that of the use of a centrifuge type of cleaning device, often combined with a pressure filter. Extensive research work in connection with the universal oil referred to above, has shown that both the transformer and switch oil often may be reconditioned after it has become contaminated, to a point where it is unsatisfactory for use. Apparatus for this purpose is now manufactured and very specific instructions have been worked out for the use of this apparatus in reconditioning and for the testing of reconditioned oil.

Parallel to the research work on the oil itself, many improvements have been made in transformer and circuit breaker designs to aid in eliminating the difficulties encountered in connection with the oil problem. It was early proved through research work that exposure of oil to the air very greatly increased its tendency to sludge and that this increase with a given exposure was more or less a function of the temperature of the oil. This led to transformer case designs, which included the conservator type of case and more recently, the inertair scheme, which automatically provides in service for the elimination of both moisture and oxygen

from contact with the oil in the transformer. While these devices have not changed the tendency of the oil to sludge under a given set of conditions, they have aided very greatly in changing service conditions, thereby inhibiting sludging and maintaining oil in a clean and dry condition.

The final result of all this work, which has extended over a period of more than 35 years, has been to make the modern transformer and circuit breaker with the universal oil, among the most satisfactory devices which goes into the modern equipment for the production, transmission, and utilization of electrical energy. The transformer and circuit breaker manufacturers, together with the oil producers who have brought about these results, realize that only eternal vigilance and continued research will make it possible to maintain and better the conditions which have been arrived at after so much labor and research in the past.

Discussion

H. B. Smith: Last November we had occasion to place 40,000 gallons of transformer oil in an open tank located under a roof. That oil was received from the refinery and when placed in the tank tested at about 36,000 volts on the standard gap. The contents of the tank were given a heat treatment, and with some centrifuging, were brought up to the value of about 42,000, about the first of December. The tank being open, the oil naturally deteriorated in dielectric strength until it had dropped to about 38,000 by the first of April this year.

We then placed in this tank at the bottom on one side, a little electric heater consuming about 3 kw., and that was applied continuously 24 hours a day. This was designed originally to start a column of warmed oil at one side that would rise and flow over the surface to produce a slightly warmer blanket of oil to maintain the surface at a slightly higher temperature than that of the air. The tendency to condense moisture from the air in the oil would then be reduced and the quality of the oil maintained so far as possible. It was found that the temperature of the oil as it reaches the surface is from 5 to 10 deg. above the air temperature.

This process was started about the first of April. Up to the first of July we found that there had been, without other heat treatment or centrifuging, an increase in the dielectric strength. The oil was brought up to about 46,000 on the standard gap. We had expected only to maintain the oil; we had not expected to increase the dielectric strength. On the first of July work had to be discontinued and the top of the tank was covered with canvas. On November 1 the oil tested slightly higher than 46,000 volts.

The only explanation of the increase in dielectric strength that I have had—and I would be glad to have comment on this,—is that this heater raises the oil at the bottom of the tank in contact with the heater elements to a point where we gradually convert any water particles into a vapor which rises with the column of warmed oil and comes to the surface. The vaporization thus creates a continuous slowly dehydrating process at a surface warmer than the air so it does not condense and recombine with the oil. This gives at the heater a temperature which does not produce cracking and a temperature at the surface in contact with the air which does not produce sludging. Whether that proves to be the explanation or not I cannot tell now. It seems a possible explanation.

J. H. Wilcox: In regard to cleaning and reconditioning oil that has been in service, Mr. Skinner says "the plan which seems to give the best results is that of the use of a centrifuge type of cleaning device often combined with a pressure filter."

Since under certain conditions this equipment will not satisfactorily recondition oil, perhaps a brief outline of the various general conditions of oil to be handled, will not be amiss here.

The impurities found in transformer oil in normal operation consist almost entirely of water and sludge. These are readily removed by passing through the centrifuge alone.

Transformer oil that has been very badly overheated or burned, as in a transformer breakdown, sometimes is so badly sludged that only chemical-centrifugal treatment will satisfactorily recondition it. The percentage of this type of oil is very small indeed as compared to that from normal operation.

The reconditioning of used circuit-breaker oil is of particular interest at this time, in view of the recent announcement by one of the largest manufacturers of transformers and circuit breakers, authorizing the use of properly reconditioned circuit-breaker oil in transformers. This eliminates the necessity of keeping reconditioned transformer and circuit-breaker oil in separate storage tanks.

The main impurities formed in circuit-breaker oil are carbon, water, and organic acid. The carbon and organic acid are caused by the arc set up in the normal operation of the breaker. Water may be introduced through leakage, condensation, and small amounts from the arcing in which the gases formed may be burned with the resultant products of combustion.

Since the finer particles of carbon are so minute that the centrifuge will not remove them, the combination of a centrifuge and blotter press is widely used for purifying circuit-breaker oil. The centrifuge removes the water and the coarser particles of carbon, and the blotterpress the finer particles of carbon.

The advantage of a combination centrifuge and blotterpress over the blotterpress alone is that by removing the water and coarser particles of carbon, several times as much oil can be put through the blotterpress before cleaning, as if the blotterpress was forced to handle all the impurities in the oil.

Organic acid builds up in the oil to a large extent in direct proportion to the amount of service to which the oil has been subjected. Very often enough moisture and carbon will form in the oil to require purification while the presence of acidity will be hardly detectable.

The combination of the centrifuge and the blotterpress will remove water and carbon satisfactorily from the oil, but will have no effect on the acidity, and oil that has either been in service for a very long time and has had repeated reconditionings with the centrifuge and blotterpress, or been subjected to very severe service, should be tested from time to time for this impurity, as high organic acidity tends to lower the resistance to emulsification and also dielectric strength.

To satisfactorily recondition circuit breaker oil with high acid content or which has been burned or carbonized so badly that it cannot be handled in the combination centrifuge and blotterpress, the following process, which is known as the Sharples chemical centrifugal process, has been developed.

The oil is heated and agitated with water-glass, which agglomerates the fine carbon particles and reduces the acidity; this mixture is then passed through a centrifuge operating as a separator, which separates out the water glass solution carrying most of the impurities.

The separated oil is then mixed with a small amount of fullers earth, which collects any remaining impurities in the oil. The fullers earth is then removed by a second centrifuge operating as a clarifier.

The operation of the process is continuous and the cost of reconditioning oil in this manner is remarkably low.

Oil reconditioned by this process will be the equal of new oil and have the following characteristics: dielectric strength, 22 kv.

or better; precise RE number, 35 seconds; neutralization value, 0.08 mg. of KOH per gram of oil; flash, fire, viscosity, and color, same as new oil.

Only oil having the above characteristics can be considered as properly reconditioned. In some cases used circuit-breaker oil is in such shape that purification by the combination centrifuge and blotterpress will not produce the desired results. Either the Sharples chemical centrifugal process should be used or the oil discarded.

Summing this all up, we have the following main types of oil and the suggested method of purifying each: Transformer oil from normal operation—centrifuge alone; transformer oil, badly sludged or burned—Sharples chemical centrifugal process; circuit-breaker oil from normal operation, satisfactory acidity—combination centrifuge and blotterpress; circuit-breaker oil, badly carbonized or high acidity—Sharples chemical centrifugal process.

This chemical treating process can be operated by the average transformer, or warehouse foreman, without any trouble whatever.

As regards costs, the average cost will run around $11.88 per 1000 gallons treated and a plant of this type will handle approximately 1000 gallons per eight-hour day.

D. W. Proebstel: I should like to say a word in regard to the refining of used oils. We had gone over this problem probably along the same lines as Mr. Wilcox and then we decided to make some short cuts.

We first considered the main elements in the refining processes that the oil companies use. In order to be brief I will say that in recovering used oil the process we used was not necessarily dependent upon a centrifuge. We use fullers earth, a tank which has a mixing device in it, steam coils, and a vacuum pump. By mixing fullers earth with the oil, subjecting the oil to heat by the steam pipes, and applying a vacuum we are able to bring the oil that ordinarily would be thrown away back to what appears to be its original condition.

With respect to flash point, fire point, viscosity, low acidity, moisture, and dielectric strength, it is a very easy process to operate and the cost of re-refining oil with us is about 6 cents a gallon.

Effect of Color of Tank on the Temperature of Self-Cooled Transformers under Service Conditions

BY V. M. MONTSINGER* and L. WETHERILL*

Member, A. I. E. E. — Associate, A. I. E. E.

Synopsis.—*The effect of color on the temperature of oil-immersed self-cooled transformers under service conditions has been a mooted question for a great many years. Based upon the relative absorption powers of the various colors often used in painting transformer tanks the lighter colors should give appreciably lower temperatures in hot climate sections. The results of three series of field tests conducted on actual transformers are given in the paper. The results, however, do not show the advantages for the light colors that would be expected, based solely upon the absorption powers of the colors.*

A method of calculation is used to check the test results, taking into consideration the various factors which apply to a transformer and do not apply to, say, a piece of metal painted and exposed to the sun's rays, such as the ratio of the area of the surface exposed to the sun to the total surface dissipating heat, the difference in thermal capacities, and the condition where in one case the test piece is dissipating heat, as well as receiving heat from the sun, whereas in the other case it only receives heat from the sun. It is shown that when all the factors are taken into consideration the calculated results check very closely the observations. Finally it is shown that the selection of color for repainting transformer tanks exposed to the sunshine should be based primarily on durability and appearance rather than upon color, since the difference in temperature resulting from a tank painted black and aluminum, or even white, will seldom exceed 1 or 2 deg. cent.

I. General

The predetermination of the ultimate temperature rise of a transformer operating in the shade, with constant load and ambient conditions is a comparatively simple problem.

Also, the effect of color on the temperature rise under these conditions can be calculated, knowing the emissivity of the color and the percentage of losses dissipated by radiation and convection for a given color.

In service, however, we have a more complicated set of conditions to deal with, which makes it more difficult to predict the effect of color on the temperature of transformers. For example, only a part of the tank's surface is exposed to the sun's rays. The part exposed is absorbing heat while the part unexposed is not affected by the sun's rays. The tank is exposed only a part of the time—during the day, while at night conditions may be altered; *i. e.*, some surfaces that are advantageous in the sunshine are disadvantageous in the shade. Also the solar intensity varies during the day which still further complicates the problem.

The impression is prevalent that a transformer tank if painted with a light color will operate at an appreciably lower temperature in the sunshine than if painted black. This impression is based either upon the relative absorption powers of the colors or upon tests made on apparatus under conditions not applicable to transformer conditions.

All tests which have been made on transformers under service conditions show, however, that the gain resulting from painting the case a light color is hardly worth considering.

The objects of this paper are (1) to give the results of the available field tests and (2) to reconcile the results of these tests with theoretical results; in other words, to show by a method of calculations, that we should not expect an appreciable gain for the light colors for the conditions under consideration.

II. Results of Tests Made Under Service Conditions

Three series of tests made under service conditions

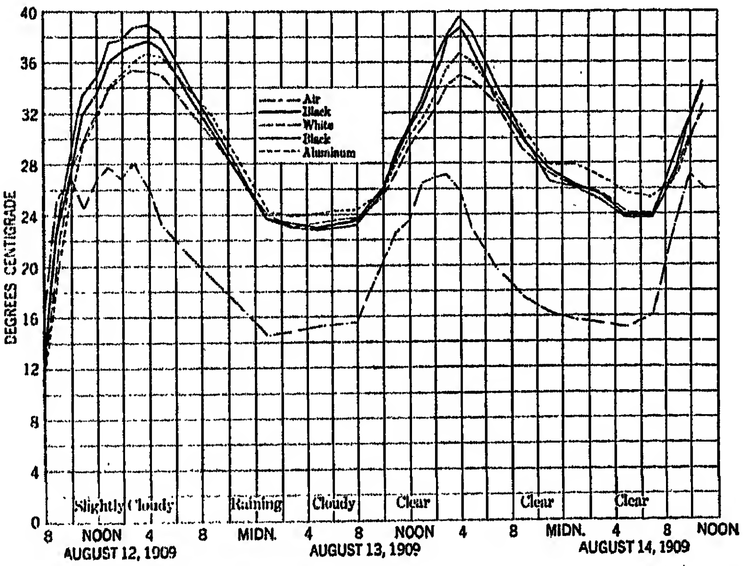

Fig. 1—Effect of Sun upon Heating of Transformers of Different Colors

Normal excitation—no load
Five kv-a. transformers with plain tanks temperature by thermometer in top oil. Tests made in Pittsfield

(at Pittsfield, Mass., Fresno, Calif., and Dallas, Texas) are given and analyzed.

Pittsfield Tests. In 1909 a series of tests was made at Pittsfield, Mass. Some 5- and 50-kv-a. lighting transformers were tested in an exposed location. Tests were made with tanks painted black, white, and aluminum. The transformers were loaded by the

*Both of the General Electric Company, Pittsfield, Mass.

Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.

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"loading back" method which insured equal loads on all pairs.

Figs. 1 and 2 show the results of tests made holding

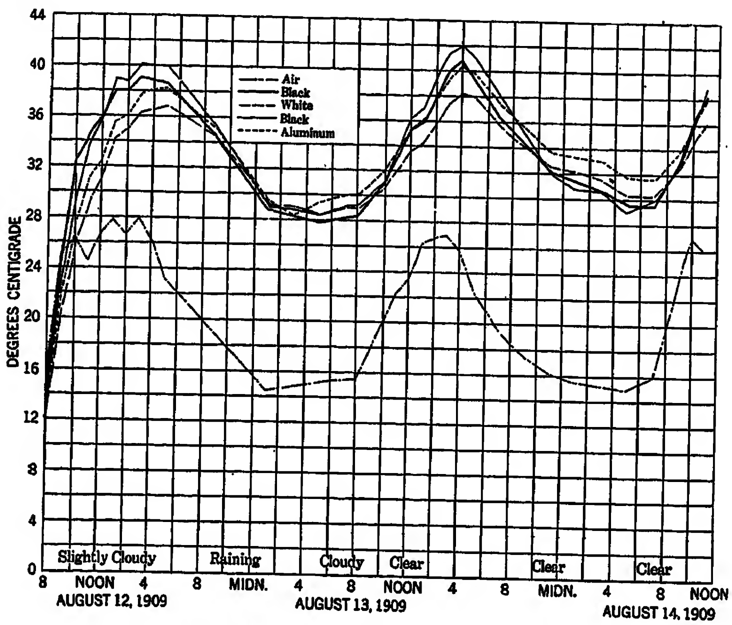

FIG. 2—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—no load
50 kv-a. transformers with cast iron corrugated tanks. Temperature by thermometer in top oil. Tests made in Pittsfield.

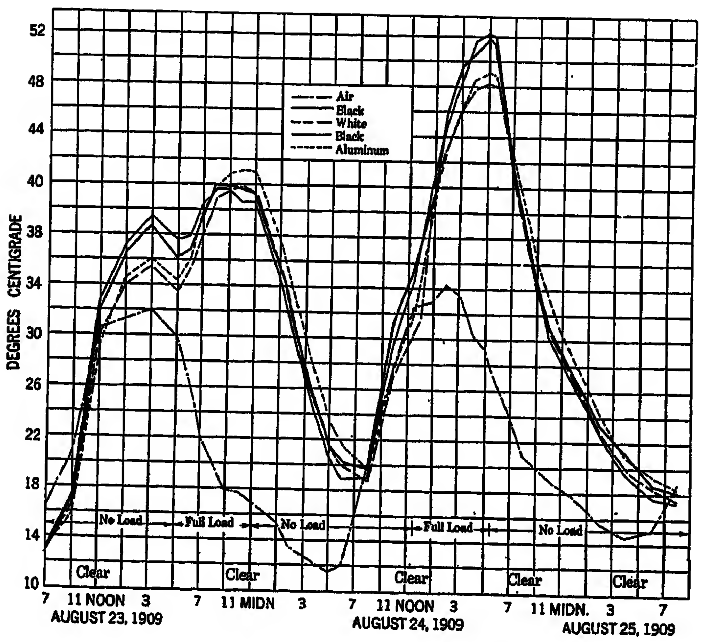

FIG. 3—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—six-hour full-load
5-kv-a. transformers with plain tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

normal excitation only on the units. It will be noticed that the transformer with the black tank averages 1 to 2 deg. cent. hotter than the one with the white tank. The maximum difference which was 4 to 5 deg. cent. occurred about 4 p. m., the black tank being the warmer. During the early morning the white tank was slightly warmer than the black one. The temperature of the aluminum painted tanks was as a rule between those of the black and white tanks.

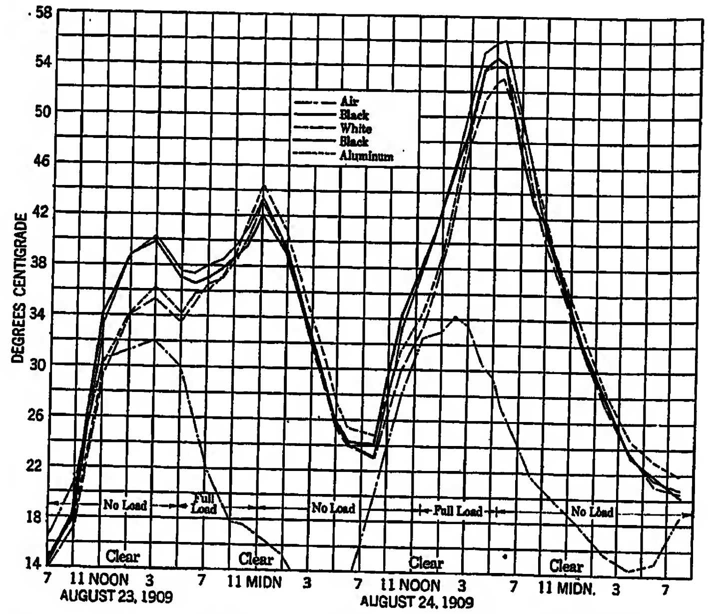

FIG. 4—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—six-hour full-load
50-kv-a. transformers with cast iron corrugated tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

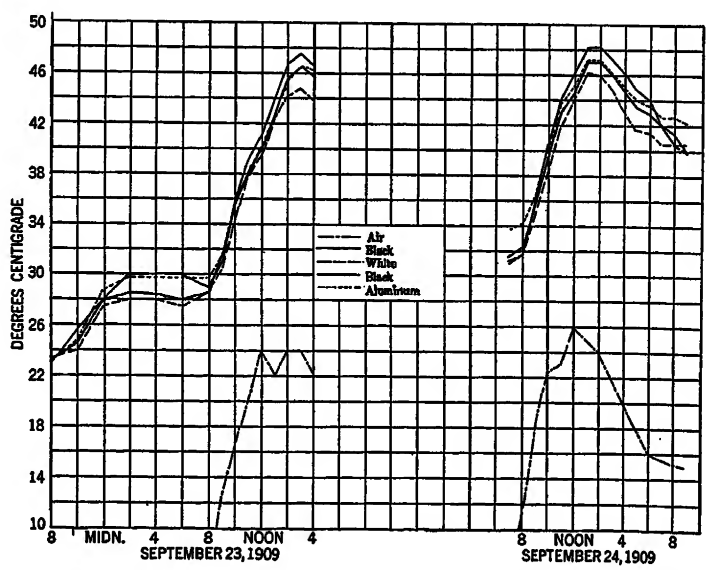

FIG. 5—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Continuous full load
5-kv-a. transformers with plain tanks. Temperature by thermometer in top oil. Tests made in Pittsfield

Figs. 3 and 4 show the results of tests made with six hour full load following normal excitation at 5 p. m. and at 11:30 a. m. The effect of the color is not quite as great in this case as in the excitation run: the maximum

difference occurring at 4 p. m. showing only 3 deg. cent. in favor of white paint over black.

Fig. 5 shows the result of a continuous full load run. The difference in temperature is still less, the maximum difference being about 2 deg. cent. Other tests also indicate that while some colors may seem to make considerable difference on light or intermittent loads, the advantage decreases considerably on continuous full load.

Fresno Tests. In 1922 Messrs. Moore and Moulton of the San Joaquin Light and Power Corporation conducted a long series of tests[1] on several 3-kv-a. lighting transformers in the sunshine at Fresno, Calif., where the air reached a maximum temperature of 38.8 deg. cent. (102 deg. fahr.).

Fig. 6 shows curves of the oil temperatures in cases of

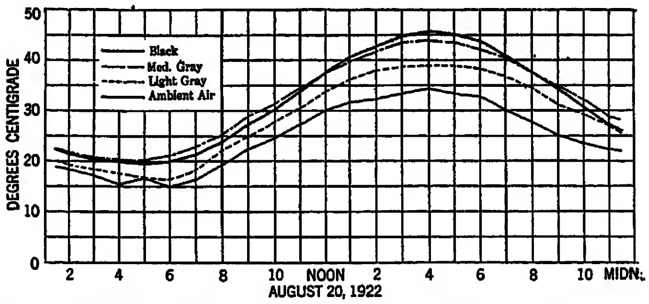

FIG. 6—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

No excitation—no load
Three kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

various colors without either load or excitation on the transformers. While these data may not be of any particular commercial value as applied to loaded transformers, since the differences in temperature will be less under load conditions, they at least indicate the relative degree to which the different colored idle transformers are affected by the sunshine.

The curves in Fig. 6 show that the average rises over the air temperature covering a 24-hr. period are as follows:

Color of case	Transformers not excited. Average rise over air	
	°F	°C
Black	12.4	6.9
Medium gray	12.9	7.16
Light gray	6.6	3.67

The fact that the medium gray is slightly higher than the black is probably caused by small mechanical differences.

Fig. 7 shows curves of temperature with the transformers excited but without load. The following average temperature rises were formed over a 24-hr. period starting 10 a. m., August 21.

1. See Bibliography for references.

Color of case	Transformers excited—No load average temperature rise over air	
	°F	°C
Black	19.5	10.8
Medium gray	21.5	12.0
Light gray	19.0	10.55

It will be noticed that the differences in temperature rise are less than without excitation.

Fig. 8 shows similar data for full load runs. The fol-

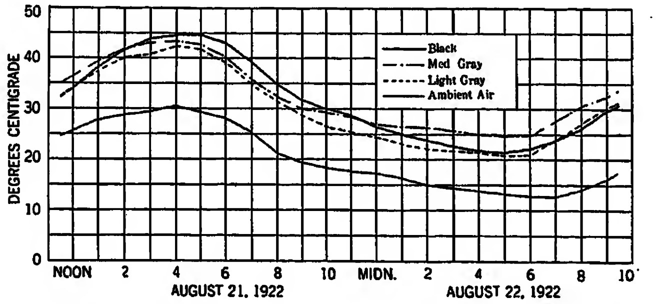

FIG. 7—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—no load
Three kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

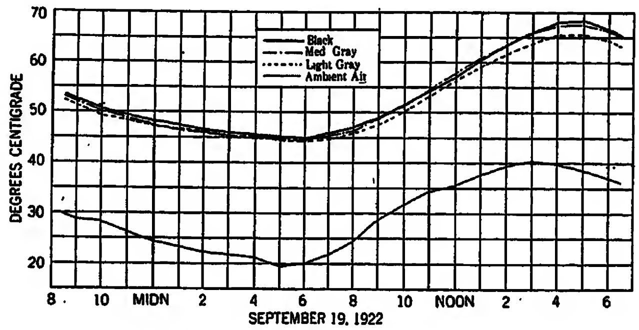

FIG. 8—EFFECT OF SUN UPON HEATING OF TRANSFORMERS OF DIFFERENT COLORS

Normal excitation—normal load
Three-kv-a. transformers with plain cases. Temperature by thermometer in top oil. Tests made in Fresno, California

lowing average temperatures were observed during a 24-hr. period starting 8 p. m., September 19.

Color of case	Average ambient		Transformers with normal load temperature rise over air			
			Deg. fahr.		Deg. cent.	
	Deg. fahr.	Deg. cent.	Avg.	Max.	Avg.	Max.
Black	85.5	29.7	43.3	53.2	24.	29.5
Medium gray	85.5	29.7	42.5	52.1	23.4	29.0
Light gray	85.5	29.7	41.0	48.6	22.8	27.0

Many more tests were made than shown above. However, the general results were the same.

The following comments are from the report by Moore and Moulton on these tests. They will be of

interest since they were made by operating engineers who have transformers operating in one of the warmest sections of the United States.

"The number of successive days during which tests were made and the consistency of the results leaves little doubt as to the accuracy of the full load tests. The fact that a gray paint will not reduce the oil temperature more than 3 or 4 deg. fahr. or 1 or 2 deg. cent. during the extremely hot weather encountered in the San Joaquin Valley seems established. This was a disappointment in view of the seemingly prevalent belief that a much larger reduction for gray paint would be found.

"We have reached the conclusion, after a very careful study of the results herein recorded, that any additional expenditure to procure a gray case instead of black would not be justified. This is in view of the fact that the differences in temperature do not under full load conditions vary any more than the difference obtained from various makes operating under identical conditions. Assuming that gray or black tanks are available at equal cost and that experience shows that gray paint stands up in service as satisfactorily as the black, we would be inclined to favor the medium gray tank. We feel very strongly however, that any expenditure to repaint black cases now in service would not in any way be justified."

Dallas Tests. Through the courtesy of Mr. O. S. Hockaday of the Texas Power and Light Company, the writers are enabled to give the results of a series of tests conducted in 1924 on three 150-kv-a. transformers with corrugated tanks painted different colors and exposed to the sun's rays. To calibrate the transformers with reference to each other, temperature of each transformer was recorded every day at 6:00 p. m. for about a month with the standard paint (aluminum with black top and bottom) on all three tanks. The average reading for each transformer showed that the northeast unit ran 1 deg. cent. cooler than the middle one and the southwest unit ran 0.3 deg. cent. cooler than the middle one.

The northeast unit was then painted all aluminum, the middle unit all black, and the southwest unit left with aluminum with black trimmings. The average results of the readings taken from July 25 to September 17 are given below. As in the calibrating run, one reading was taken at 6 p. m. each day. Fair weather occurred during 80 per cent of the test period.

From July 25 to September 17 inclusive the average temperatures are:

	Northeast all aluminum	Middle all black	Southwest alum. black trim.
Observed temperature........	47.7	49.6	49.1
Correction from calibrating run	1.0	0	0.3
Corrected temp. (deg. cent.)..	48.7	49.6	49.4

Thus the all-aluminum runs 0.9 deg. cent. cooler than the black.

That the 20 per cent of cloudy or rainy weather has not had any great effect can be seen from the three following sets of figures each based on seven consecutive days of fair weather.

From August 6 to 12 inclusive the average temperatures are:

	Northeast all aluminum	Middle all black	Southwest alum. black trim
Observed temperature........	49.1	50.4	50.1
Average correction from calibrating run...............	1.0	0	0.3
Corrected relative temp... ...	50.1	50.4	50.4

In this case the all aluminum runs 0.3 deg. cent. cooler than the black.

From August 18 to 25 inclusive, the average temperatures are:

	Northeast all alum.	Middle all black	Southwest alum. black trim std.
Observed temp...	50.5	52.5	52
Average correction from calibrating run...............	1.0	0	0.3
Corrected relative temp.......	51.5	52.5	52.3

In this case, the all aluminum ran 1.0 deg. cent. cooler than the all black whereas the aluminum black trimming ran 0.2 deg. cent. cooler.

From August 28 to September 10 inclusive, the average temperatures are:

	Northeast all alum.	Middle all black	Southwest alum. black trim
Average observed temp..	48.3	51.7	51.0
Correction..................	1.0	0	0.3
Corrected relative temp.......	49.3	51.7	51.3

The all aluminum ran 2.4 deg. cent. cooler and the aluminum black trim ran 0.4 deg. cent. cooler than the all black tank.

Table I gives the results of readings taken every half hour from 10 a. m. to 6 p. m., October 1. Based on the average readings corrected, the all aluminum tank ran 0.7 deg. cent. cooler and the aluminum-black trim ran 0.5 deg. cent. warmer than the all black tank. This last set of readings is perhaps the most reliable since it took account of the entire day and afternoon when the aluminum color shows up to best advantage.

Pittsfield Tests on Aluminum Tanks. The preceding tests showed a slight advantage for aluminum but they were made under circumstances favorable to aluminum. Tests made with the tanks shaded from the sun show the disadvantages of aluminum.

Some tests were made in Pittsfield in 1925 to show the

TABLE I

TESTS MADE BY TEXAS POWER AND LIGHT COMPANY

Three Transformers–150 Kv-a., Corrugated Tanks, Bank Capacity 450 Kv-a.

Time	Kv-a.	Ambient temperature	Transformer temperature		
			Aluminum	Black	Alum. black trim.
10:00 a. m.	394	23	31	33	32
10:30	394	23	31	34	33
11:00	396	23	32	34	33
11:30	425	24	33	35	34
12:00 m.	445	25	34	36	35
1:00 p. m.	360	27	36	37	37
1:30	343	28	36	38	37
2:00	373	29	37	38	38
2:30	370	29	37	38	38
3:00	365	29	38	39	38
3:30	357	29	38	39	39
4:00	324	28	39	40	40
4:30	321	27	39	40	40
5:00	376	26	38	40	39
5:30	384	24	38	40	39
6:00	374	22	37	39	39

Data furnished through the courtesy of O. S. Hockaday of the Texas Power and Light Company.

effect of aluminum paint on operation in the shade (indoors) on two standard 25-kv-a. transformers having plain cases.

Two units having the same losses were first tested with their tanks painted black. The two tanks were then painted aluminum and the test repeated with results shown below.

Transf. No.	Room temp. deg. cent.	Top oil rise deg. cent.		Max. tank surf. rise deg. cent.	
		Black	Alum.	Black	Alum.
1	26	37.2	46.3	32.5	41.0
2	26	36.7	47.6	32.0	41.6
Average	26	37.	47.	32.3	41.3

The oil rise of the aluminum tank was 126.5 per cent of the black tank. The maximum tank surface rise of the aluminum tank was 126 per cent of the black tank. This checks very well the estimated percentage of about 130 per cent, assuming a low temperature emissivity of 0.55 for aluminum paint.

The effect of aluminum paint in increasing the temperature indoors is lessened on radiator and tubular tanks, but may still be appreciable. A tank with four rows of tubes will run by calculation about 12 per cent hotter with aluminum paint when operating in the shade. Even on the largest tanks with radiators as close to each other as possible, it is estimated that aluminum paint will increase the temperature rise about 7 per cent when operating in the shade.

III. Development of Method of Calculating Effect of Color

In considering the effect of the sun's rays on a transformer it must be remembered that the radiant heat received is only that passing through the projection of the transformer on a plane perpendicular to the sun's rays. In order to predict the effect of the sun it would be necessary not only to know the strength of the sun's rays as a function of the time of day, but also to know the projection of the tank on a plane perpendicular to the sun's rays as a function of the time of day. It would be possible to do this, but this laborious process can be avoided.

Instead of taking readings of the sun's intensity on a plane perpendicular to its rays and correcting for the variation in projected area of the transformer in order to correlate the sun's intensity with the behavior of a transformer with a special finish, it is possible to use a similar transformer with a standard black paint for an instrument to measure the effect of the sun. This effect as determined, will be automatically corrected for variation in the projected surface and its relation to the total surface effective in dissipating heat. The effect will be expressed as, r, the average solar intensity in watts

*TABLE II

LOW TEMPERATURE TOTAL EMISSIVITIES

Silver, highly polished	0.02
Platinum " "	0.05
Zinc " "	0.05
Aluminum " "	0.08
†Monel metal, polished	0.09
Nickel "	0.12
Copper "	0.15
Stellite "	0.18
Cast iron "	0.25
Monel metal, oxidized	0.43
Aluminum paint	0.55
Brass, polished	0.60
Oxidized copper	0.60
Oxidized steel	0.70
Bronze paint	0.80
Black gloss paint	0.90
White lacquer	0.95
White vitreous enamel	0.95
Asbestos paper	0.95
Green paint	0.95
Gray paint	0.95
Lamp black	0.95

*These data are the result of investigations made by the Bureau of Standards, the British National Physical Laboratory, General Electric Research Laboratories, and several eastern universities, and were collected by W. J. King of the General Electric Co.

†Questionable because of scant or inconsistent data.

*TABLE III

COEFFICIENT OF ABSORPTION OF SOLAR RADIATION

Silver, highly polished	0.07
Platinum " "	0.10
Nickel " "	0.15
†Aluminum "	0.15
Magnesium carbonate	0.15
Zinc oxide	0.15
†Steel	0.20
Copper	0.25
White lead paint	0.25
Zinc oxide paint	0.30
Stellite, polished	0.30
Light cream paint	0.35
Monel metal, polished	0.40
Light yellow paint	0.45
Light green paint	0.50
Aluminum paint	0.55
Zinc, polished metal	0.55
Gray paint	0.75
Black matte	0.97

*These data are the result of investigations made by the Bureau of Standards, the British National Physical Laboratory, General Electric Research Laboratories, and several eastern universities, and were collected by W. J. King of the General Electric Co.

†Questionable because of scant or inconsistent data.

per sq. cm. of effective tank surface. The same curve will hold for any transformers having similar tanks and similar locations close by. The behavior of any such similar transformers can be calculated if their losses, thermal characteristics, and initial temperature are known, as well as the manner of variation of ambient temperature.

The following symbols will be used:

C = Thermal capacity in joules per sq. cm. per degree centigrade divided by 3600.
E = Coefficient of total emissivity at low temperature.
F = Ratio of average tank surface temperature rise over ambient to top oil rise over ambient.
L = Transformer loss in watts per sq. cm.
P = Pressure in atmospheres.
r = Effective intensity of solar radiation in watts per sq. cm. of effective surface.
r_a = Average value of r over one hour period.
S = Coefficient of solar absorption. See Table III.
T_o = Top oil temperature in degrees Kelvin.
T_{oa} = Average value of T_o over one hour period.
T_{oi} = Value of T_o at beginning of one hour period.
ΔT_o = Change in T_o in one hour.
T_1 = Temperature in degrees Kelvin of surface absorbing heat radiation.
T_{1a} = Average value of T_1 over one hour period.
T_2 = Temperature in degrees Kelvin of surface radiating heat.
t = Time in hours.
W_C = Watts per sq. cm. dissipated by convection.
W_R = Watts per sq. cm. dissipated by radiation.
W_T = Watts per sq. cm. dissipated by radiation and convection.

It is shown in Appendix A that the following empirical expression can be used for the total loss by convection and radiation from a vertical plane in watts per sq. cm.

$$W_T = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} \quad (1)$$

Equation (2) is the general differential equation for the thermal behavior of a self-cooled transformer, subjected to the rays of the sun.

$$S\,r + L = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} + C \frac{d\,T_o}{d\,t} \quad (2)$$

The approximate expression for the total heat dissipated given in Equation (1) is used. In the term containing the thermal capacity, C, the top oil temperature, T_o, is used as the thermal capacity has been worked out on that basis,[2] although not all of the oil and tank is actually that hot. In the expression for heat dissipation the tank surface temperature T_2 is used. In the cases analyzed the tank surface temperature is not available, so the tank surface rise is assumed to be proportional to the top oil rise.

Thus:

$$T_2 - T_1 = F(T_o - T_1) \quad (3)$$

$$T_2 = F\,(T_o - T_1) + T_1 \quad (4)$$

Substituting this expression for T_2 in Equation (2) gives Equation (5).

$$S\,r + L = 6.50 \times 10^{-4} F^{1.19} (T_o - T_1)^{1.19} + C \frac{d\,T_o}{d\,t} \quad (5)$$

As the data consist of hourly readings we assume that the differential equation holds for average values over a one-hour period. Any errors caused by this assumption are too small to have any effect.

In what follows intervals of one hour will be considered; T_{oa}, T_{1a}, and r_a will be used to represent average values over a period of one hour and the average value of $\frac{d\,T_o}{d\,t}$ will be represented by ΔT_o, the change in T_o on one hour.

Rewriting Equation (5) to use average values gives

$$S\,r_a + L = 6.50 \times 10^{-4} F^{1.19} (T_{oa} - T_{1a})^{1.19} + C\,\Delta T_o \quad (6)$$

This is not in a convenient form because both T_{oa} and ΔT_o are unknown. For T_{oa} substitute T_{oi}, the initial value, plus $\Delta T_o/2$; which gives the average value, assuming linear variation.

$$S\,r + L = 6.50 \times 10^{-4} F^{1.19} \left(T_{oi} + \frac{\Delta T_o}{2} - T_{1a} \right)^{1.19} + C\,\Delta T_o \quad (7)$$

This can be simplified by expanding $[(T_{oi} - T_{1a}) + \Delta T_o/2]^{1.19}$ by the binomial theorem and dropping the third and subsequent terms.

$$S\,r_a + L = 6.50 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{1.19} + \frac{1}{2} 6.50 \times 10^{-4} \times 1.19 F^{1.19} (T_{oi} - T_{1a})^{0.19} \Delta T_o + C\,\Delta T_o \quad (8)$$

Solving Equation (6) for F and r_a, and Equation (8) for ΔT_o gives Equations (9) (10), and (11).

$$F = \left(\frac{S\,r_a + L - C\,\Delta T_o}{6.50 \times 10^{-4} (T_{oa} - T_{1a})^{1.19}} \right)^{.84} \quad (9)$$

$$r_a = \frac{6.50 \times 10^{-4} F^{1.19} (T_{oa} - T_{1a})^{1.19} + C\,\Delta T_o - L}{S} \quad (10)$$

$$\Delta T_o = \frac{S r_a + L - 6.50 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{1.19}}{C + 3.88 \times 10^{-4} F^{1.19} (T_{oi} - T_{1a})^{0.19}} \quad (11)$$

Equations (9), (10), and (11) are sufficient to handle cases where hourly readings are available.

In order to calculate the top oil temperature of a transformer with a special coat of paint operating in the sunshine, it is necessary to have the following information.

(a) Hourly readings of the ambient temperature during the period of the test.

(b) The initial temperature of the test transformer.

(c) Hourly readings of the top oil temperature of an indicating transformer with a tank and location similar to the test transformer. The indicating transformer

probably does not need to be identical with the test transformer or to carry the same load, although in the tests referred to later this was done for convenience.

(d) Effective surface, losses, and thermal capacity of the two transformers. Strictly speaking, the effective surface is not required as a study of the equations will show that any surface area may be assumed and the constant F will come out of such a value as to correct the results. In this paper the actual effective surface is used to show more clearly the physical significance of the mathematical steps.

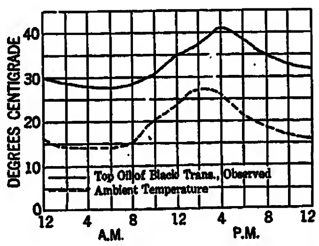

FIG. 9—NO-LOAD HEAT RUN

Made on 50 kv-a. transformers exposed to sun at Pittsfield. A black corrugated tank was used

Having these data the process of solution may be summarized in the following steps.

(a) Apply Equation (9) to the identical transformer with standard paint for a period of one hour during which the transformer receives no solar radiation. This may be taken from operation at night, indoors or in the shade. From Equation (9) calculate F. It is well to take several hours and use the average value of F.

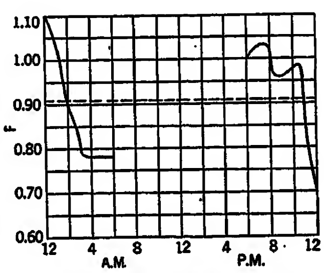

FIG. 10—VALUES OF CONSTANT F

Ratio of tank rise to top oil rise, for 50 kv-a. transformers during period in which solar intensity is zero. Dotted line gives average value

(b) Apply Equation (10) to a transformer with a coat of standard paint having a low temperature emissivity, E, of 0.95 and a known co-efficient of solar absorption, S. This transformer must be similar to the one with the paint under test in the construction of the tank and in location. They must both have the same situation with respect to the sun. Equation (10) should be applied to the tank with the standard finish during the portion of the test in which the tanks are receiving solar radiation, about 6 a. m. to 6 p. m. From Equation (10) r_a is determined for each one-hour period.

(c) Apply Equation (11) to the transformer with the paint undergoing test, the behavior of which is to be determined. F was determined as given in paragraph (a). During the hours in which the tank received sunlight r_a was determined as given in paragraph (b). At other times r_a is zero, as the tank is receiving no solar heat. Start with the initial top oil temperature T_{oi} and calculate the change $\Delta\, T_o$ by Equation (11). Then $T_{oi} + \Delta\, T_o$ gives the final temperature at the end of the hour, which becomes the initial temperature for the following hour. The process is repeated, each time giving a new value of T_o one hour after the last, until the end of the test period is reached.

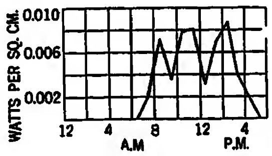

FIG. 11—WATTS PER SQ. CM. INTENSITY OF SUN

As determined from data on 50 kv-a. transformer with black tank. Average intensity over effective surface is used

IV. CALCULATION OF EFFECT OF COLOR

The first example selected for calculation is the data for August 13, shown in Fig. 2. Two 50-kv-a. transformers with corrugated tanks operated at normal excitation and no load. The curve for the black tank is shown on a larger scale in Fig. 9.

The calculation of F, the ratio of tank surface rise to top oil rise, for the hours before sunrise and after sunset is plotted in Fig. 10. The average value is 0.92. Cooney[2] gives the average value of this constant as 0.85 for all self-cooled transformers.

Fig. 11 gives the calculation of r_a, the effective intensity of solar radiation, during the daylight hours. The points are not all accurate as the data were taken only to the nearest half degree, and two- or three-tenths of a degree is enough to cause considerable variation in r_a. Such an error is not serious as an equal error in the other direction will occur in the next hour and counteract the effect of the first one.

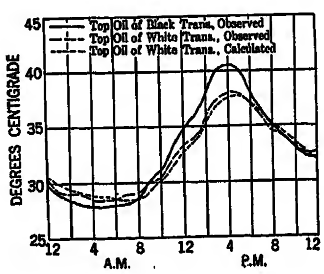

FIG. 12—COMPARISON OF TOP OIL TEMPERATURE OF 50-KV-A. TRANSFORMERS OPERATING IN SUN

The calculation of the top oil temperature of the second transformer which is painted white ($S = 0.30$) is plotted in Fig. 12 and compared with the observed values. The top oil temperature of the black transformer is also plotted, to show that the calculated

curve has really taken care of the effect of the color and come decidedly closer to the observed curve of the white transformer than that of the black one.

The second example selected for calculation is the data shown in Fig. 8 for September 19. Black and light gray cases were used. Two 3-kv-a. transformers were run at full load in the sun.

Figs. 13 to 16 give the data, calculations, and results.

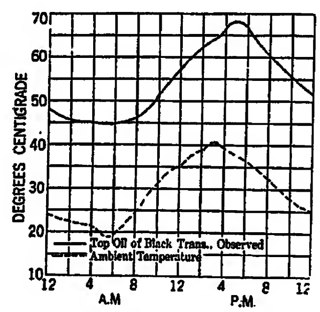

Fig. 13—Full Load Heat Runs

Made on three-kv-a. transformers exposed to sun, by San Joaquin Light and Power Corporation at the Fresno O. Street Substation, September 19, 1922. A black smooth tank was used

The agreement shown in Fig. 16 between calculated and observed top oil temperature is as close as can be expected.

In this case the transformers were carrying full load and L, the loss per sq. cm. of effective tank surface, varies with the temperature. As the variation in loss is not very great it is sufficient to use the loss corresponding to the coil rise over oil (15 deg. cent. in this case) plus the top oil temperature at the beginning of the one-hour period.

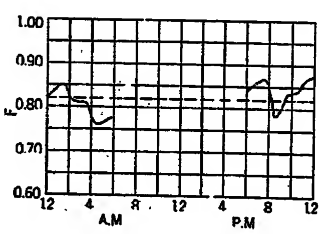

Fig. 14—Values of Constant F

Ratio of tank rise to top oil rise, for three kv-a. transformers during period in which solar intensity is zero. Dotted line gives average value

It is possible to show that the maximum values of r_a are about the right order of magnitude to agree with the intensity of solar radiation. The ratio of the sun's intensity to r_a should be approximately the ratio of the effective surface to the projected area of the tank on a plane perpendicular to the sun's rays.

The maximum intensity of the sun's rays on a clear day at sea level[3] is about 0.094 watt per sq. cm. Corrugated tanks were used at Pittsfield, so we would expect the effective surface to be on the order of ten imes the projected surface, which would mean that r_a would be one-tenth of the solar intensity. Actually the maximum value of r_a is 0.0089 watt per sq. cm. while one-tenth of the maximum solar intensity is 0.0094 watt per sq. cm.

In the California tests smooth tanks were used and we would expect that the maximum value of r_a would be about one-sixth of the maximum solar intensity. The maximum value of r_a is 0.0091 while one-sixth of the solar intensity is 0.0157. These figures give as close a check as we can expect without actually recording the intensity of the sun at the time.

The chief sources of error in the method used is the

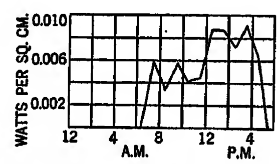

Fig. 15—Watts Per Sq. Cm. Intensity of Sun

As determined from data on three-kv-a. transformer with black paint. Average intensity over effective surface is used

possibility of small mechanical differences in the two transformers used giving them slightly different thermal characteristics, and the effect of wind. Mechanical differences will not often cause more than one or two degrees error and usually less than one degree. If there should be a discrepancy the possibility of error due to mechanical differences could be investigated by making heat runs on the two transformers. In the cases investigated very little discrepancy was found so we must conclude that the pairs of transformers were very nearly identical.

The wind may affect the results a great deal as a small

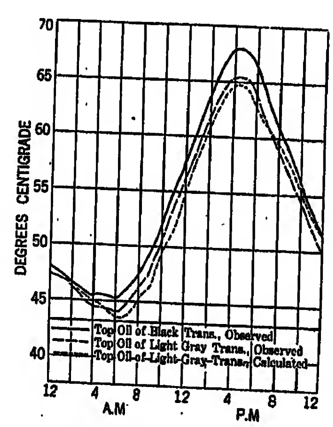

Fig. 16—Comparison of Top Oil Temperature of Three Kv-a. Transformers Operating in Sun

amount of wind will greatly increase the convection loss by disturbing the air film adhering to the tank surface. Errors due to wind, if it is present, appear as errors in the curve of r shown in Fig. 12. When the resulting incorrect curve of r is used to calculate the behavior of the second transformer the error is partly compensated

for. However, this method of calculating could not be expected to give good results on a windy day.

One reason why it is possible to consider average values over a period of an hour is that the method automatically corrects the resulting errors. If the first step results in an error making the transformer too hot, the transformer will dissipate too much heat later and counteract the effect. An error caused in any way will gradually die out.

V. Conclusions

A. In Shade.

1. The temperature rise of a transformer in a tank

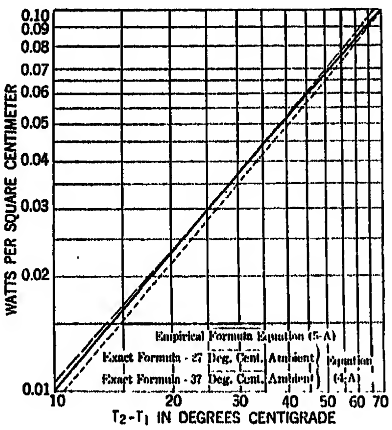

Fig. 17—Comparison of Empirical and Exact Formulas for Total Heat Dissipated

painted with a non-metallic paint is practically independent of the color.

2. Metallic paints radiate less heat than non-metallic paints and may cause a transformer to over-heat.

3. A plain aluminum painted tank will run approximately 30 per cent higher temperature rise* than if painted with a non-metallic paint.

4. Thirty per cent represents the maximum increase of temperature rise caused by painting a tank with aluminum instead of a non-metallic paint. If a plain tank is finished with a surface having a lower emissivity than aluminum the temperature increase naturally will be more than 30 per cent, increasing to about 75 per cent* where the emissivity is very low such as for polished silver, nickel, etc.

5. As the surface of a tank becomes more and more convoluted (with tubes and externally connected radiators) the effect of a metallic paint in increasing the temperature rise becomes less and less, in extreme cases getting as low as 7 per cent.*

B. In Sunshine.

1. The improvement resulting from using special paint on self-cooled transformer tanks either plain or with convoluted surfaces is in service very small, hardly enough to be worth considering. Even under the most favorable conditions (white lead paint, smooth tank surface, and a hot sunny day) the gain is not more than 2 deg. cent. average during a 24-hr. period and in some cases less than 2 deg. cent.

2. The repainting of transformer tanks in the field for operation in the warmer sections of the country should be based upon the consideration of durability and appearance rather than upon color.

Appendix A

Heat energy is dissipated from a surface exposed to the air in two ways, convection and radiation. The losses of heat energy by these two methods are independent and may be calculated separately.

It has been shown that the convection[4] loss from transformer tanks can be expressed with fair accuracy by the equation:

$$W = 2.17 \times 10^{-4} P^{1/2} (T_2 - T_1)^{1.25} \qquad \textbf{(1a)}$$

This equation gives the loss from a vertical surface and its application must be limited to vertical surfaces of reasonable heights.

The heat energy dissipated by radiation[5] is given by the Stefan-Boltzman law:

$$W_R = 5.7 \times 10^{-12} E (T_2^4 - T_1^4) \qquad \textbf{(2a)}$$

In this equation E is the coefficient of total emissivity. For most non-metallic paints the value is 0.95 approximately.

The total heat dissipated from a plain surface W_T is the sum of the two.

$$W_T = 2.17 \times 10^{-4} P^{1/2} (T_2 - T_1)^{1.25} + 5.7 \times 10^{-12} E (T_2^4 - T_1^4) \qquad \textbf{(3a)}$$

If P is one atmosphere and E is 0.95 Equation **(4a)** results:

$$W_T = 2.17 \times 10^{-4} (T_2 - T_1)^{1.25} + 5.4 \times 10^{-12} (T_2^4 - T_1^4) \qquad \textbf{(4a)}$$

Equation **(5a)** is a much simpler approximate expression for W_T.

$$W_T = 6.50 \times 10^{-4} (T_2 - T_1)^{1.19} \qquad \textbf{(5a)}$$

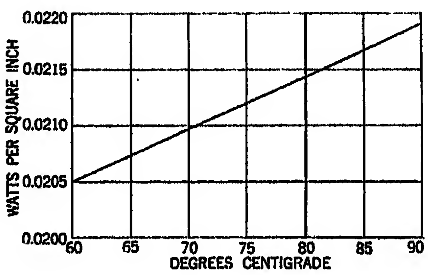

Fig. 18—Watts Loss Per Sq. Cm. of Tank Surface at Full Load *vs.* Winding Temperatures—for Three-Kv-a. Transformers

The close agreement existing between the exact and empirical expressions is best shown graphically. In Fig. 17 the dotted and dashed lines represent the amount of heat dissipated from a vertical surface for ambient temperature of 27 deg. cent. and 37 deg. cent. respectively, according to Equation **(4a)**. The solid

*Refers to oil rise. The winding rise over room will be increased the same number of degrees as the oil rise is increased.

line is obtained by using Equation (5a). It is seen that over the operating range the empirical expression gives satisfactory results.

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Discussion

W. C. Smith: It is evident, from data submitted in the paper, that the operators who are using aluminum paint, and who have standardized it over their entire system, should immediately change over all indoor self-cooled transformers, or those shaded from the sun, to some other color such as gray.

The thought has occurred to me, and I believe there are some data existing on the point, that the use of sunshades in the desert localities in this part of the country would be very beneficial.

If anyone has that information at hand, I should appreciate a word on the matter, as I know from actual test that the effect of the sun beating down on a transformer tank will raise its temperature at least 20 to 30 deg. over the ambient shade temperature.

In conditions such as exist in the Imperial Valley, it would seem desirable perhaps to bring out the high-tension connections horizontally to a sufficient distance to allow of a sunshade, protecting the transformers from the hotter day temperatures, and then paint the tank a non-metallic dark color.

C. H. Holladay: We have had a few experiments on the effect of the color, not on the transformer tanks, as shown in this paper, but on our Florence Lake Dam at Big Creek. To prevent entrance of water the surface of the dam, about 400,000 sq. ft., was painted with black bituminous paint. After it had been on several years it was noticed that the paint had deteriorated in a number of places and had come off in small flakes. It seemed that possibly it was due to the heating effect of the sun on the black surface.

To determine the amount of this heating, the bulb of a recording thermometer was grouted into the concrete on the face of one of the arches. Into the face of the next arch we grouted another thermometer bulb and painted the area around it, 10 ft. by 10 ft., with one coat of aluminum paint. A third thermometer recorded the air temperature.

The daily temperature curves from these three thermometers are very interesting. When there was sunlight on the face of the dam, the black surface became very much hotter than the air or the aluminum surface. On a typical clear day in November, the three temperatures are the same at 8 a.m. The peak is reached at about 1 p.m. with a black-surface temperature of 107 deg. fahr., aluminum 64 deg., and air 50 deg. After 3 p.m. the temperatures drop very rapidly though there is enough heat stored in the concrete to keep it about 10 deg. above the air. Even on a cloudy day there is as much as 6 deg. difference between the aluminum and black.

We made still another series of tests to determine the difference in temperature on the interior of cottages when the roofs are painted with aluminum and with dark paint. Two identical cottages having the same exposure were chosen. The roof of one was painted with our standard dark brown paint, while the other roof was painted with aluminum. We then took daily temperature charts in both houses.

In the day the temperature of the house with the dark roof was 3 to 6 deg. fahr. above that with the aluminum roof. During the summer both houses would come to a peak at about five in the afternoon. At night the house with the dark roof cooled off faster and reached a temperature of three deg. fahr. below the house with the aluminum roof.

J. F. Dunn: We should like to call attention to the statement that the results of the tests show such a slight difference between light and dark paints as effecting final temperature that it is "hardly worth considering." In the results of the Pittsfield tests the statement is made that the transformer with the black tank averages 1 deg. to 2 deg. cent. hotter than the one with the white tank. A maximum difference which was 4 deg. to 5 deg. cent. occurred about 4 p.m., the black tank being the warmer. Most of us are familiar with the emphasis placed by transformer manufacturers on the rise of temperature and also with the fact that for a slight decrease in rise of temperature for a given output we pay a higher price for the apparatus. In view of this, the offhand manner in which the authors deem the saving of an average say of 2 deg. cent. and a maximum of say 4 deg. cent. in temperature rise is surprising, especially in view of the fact that when transformers are subjected to the acceptance temperature run the manufacturers insist on correcting the rise for the viscosity of the cooling oil, which under the worst conditions would amount to not more than 1 deg. cent.

This average difference of say 2 deg. cent. in the relation between oil temperature and output rating of the transformers may amount to 5 per cent or more in the maximum percentage of safe load on the transformer for a given hottest oil temperature. This fact is brought out in a very interesting way in the recent paper by E. T. Norris entitled *Safe Loading of Oil Immersed Transformers*, (A. I. E. E. Quarterly TRANS., Vol. 48, October 1929, p. 1206). The slope of the curve developed by Mr. Norris as shown in Fig. 4, giving the relation between hottest oil temperature and maximum percentage safe load for a given case shows up as one-half, or for a given maximum temperature rise an increase of percentage of safe load in the ratio of 1 to 2.

It should be further noted that the experiments showing this average of 2 deg. cent. were conducted at Pittsfield, Mass. and that for southern and tropical countries where the intensity of the sun's rays is considerably greater, we should have a corresponding increase in the average temperature between light-colored and dark-colored transformers. The experiment made in Texas should not be considered seriously because of the fact that one reading per day was taken at 6 p.m., when the minimum difference was to be expected between light and dark colors and the transformers were not properly calibrated. The difference noted in the calibrating run might possibly be caused by mechanical and electrical differences in the transformers and not be due to position or radiation. The difference between the light and dark colors obtained in California as shown in Fig. 6 may be noted as 6 deg. cent. at 4 p.m. as against 4 deg. cent. at 4 p.m. in Fig. 2 and 4½ deg. cent. at 4 p.m. in Fig. 1. Figs. 1 and 2 were taken at Pittsfield and Fig. 6 was taken in California some 500 miles nearer the equator. This illustrates the point made above as to the results to be expected in the warmer territory. We are much interested in aluminum paint for transformers in very warm climates and hope that some further experiments will be conducted either to prove or disprove its desirability for use in these localities. Unfortunately, the experiments in California did not include aluminum paint.

There seems to be a discrepancy between the conclusions of the authors as given on the ninth page under "A: In shade," paragraph 5 which is quoted as follows: "As the service of the tank becomes more and more convoluted (with tubes and externally connected radiators) the effect of a metallic paint in increasing

oil temperature becomes less and less, in extreme cases getting as low as 7 per cent," and the results and conclusions reached by the late John R. Allen, a noted heating and ventilating engineer. These results and experiments are recorded in Vols. 24 and 26 of the *Journal* of the American Society of Heating and Ventilating Engineers, pp. 274 and 109 respectively. He states that "In radiators having a large proportion of rating surface such as pipe coils or wall coils, the effect of paint will be more marked than in 4-column radiators having a comparatively small radiating surface in proportion to the convecting surface."

All finely ground materials have about the same radiation constant; therefore all paints made from finely ground pigments will have the same effect. Metals have a poor radiating effect so that any paint involving a flake metal such as bronze will have a low radiating constant.

J. S. Moulton: This paper supplements the field data previously available with calculations confirming the several field tests referred to. It is gratifying to have such calculations confirm the tests made by Mr. L. J. Moore and me during 1922. At that time, we concluded that the repainting of transformers when received from the manufacturers, or when taken down from service, was not justified by any improvement in temperature characteristics secured by the use of a light colored paint.

The data of Messrs. Wetherill and Montsinger show that paint may be selected for its durability in service, or to conform with a distinctive color scheme, if one is in effect, without consideration of resulting effect upon the temperature.

V. M. Montsinger: The discussion of Mr. Dunn criticizes the Dallas tests because of the fact that readings were taken at 6 p. m. instead of at the hottest part of the day. While the latter would have been preferable, it will be noted from Table I that the conclusions would not be altered to any essential degree.

I note that he has compared the black and white tank with normal excitation only on the transformers at Pittsfield. Comparing these tanks with continuous full load, Fig. 5, the maximum difference is 2 deg. cent. instead of 4 to 5 deg. cent. All the tests show that the difference decreases as the temperature increases. This is pointed out in the paper. Furthermore, the difference between the black and aluminum is about one-half the difference between that of black and white, meaning that the maximum difference is about 1 deg. cent. under full-load conditions. The average difference is probably less than 1 deg. cent. Factory tests are made under full load conditions rather than under no-load conditions.

Mr. Dunn has taken the curve in Fig. 4 of Mr. E. T. Norris' paper to prove that for a difference of 2 deg. cent. in oil the load may vary 5 per cent. This curve does not attempt to show how the load varies with temperature rise but rather the difference in temperature between the oil and hot spot as the load increases. For the purpose of illustration, Mr. Norris assumes that at 100 per cent load the hot spot rise over the oil is 20 deg. cent., and that the hot spot should not exceed 105 deg. cent. For 100 per cent load the oil then should not exceed $(105 - 20) = 85$ deg. cent. For 140 per cent load the hot spot rise is $20 \times \left(\frac{140}{100}\right)^2 = 39.2$ deg. and the oil, therefore, should not exceed $(100 - 39.2) = 65.8$ deg. cent. In other words, when the oil reaches the value shown on this curve for any given load the load should either be reduced or removed. This is quite different from the way in which Mr. Dunn has used it.

Answering the point in question, namely, the variation in per cent load with temperature rise, calculations made by the proper formula will show that the load can be increased about 1 per cent or slightly more for each 1 deg. cent. increase in hot-spot temperature. This question will be discussed in detail by the writer in a paper entitled *Loading Transformers by Temperature* to be presented at the Winter Convention, 1930.

With reference to our conclusions and the late John R. Allen's conclusions on the effect of color in the shade on tanks with varying ratios of radiating and convecting surfaces, if he quotes Mr. Allen correctly there is no disagreement. Both say the same thing, but in a different way. I should like to point out that our data do not show that the light colors cause as large an increase in the temperature in the shade as is shown by Mr. Allen's data. We are unable to explain how Mr. Allen obtained such large differences. The most reliable emissivity factors do not check these results. In fact, recent tests reported by C. H. Fessenden and Axel Marin in an article entitled "New Data on Heating Effect of Painting Tubular Radiators" in *Heating and Ventilation Magazine*, February 1929, show much smaller differences than those claimed by Mr. Allen.

The following is quoted from p. 64 of this report:

"Prof. John R. Allen presented a paper about 18 years ago in which it was reported that paints having a flake-metal base when applied to a cast-iron rectangle reduced the heat emission of the radiator as much as 25 per cent. Although the statement frequently has been made that the form and distribution of the surface of the radiator would influence such quantitative data, the erroneous impression seems to be rather widespread that aluminum paint reduces the effectiveness of *any* radiator by about 25 per cent."

These invesitgators found that the difference between an unpainted radiator and one painted with aluminum was in the order of 7 to 8 per cent. The largest difference they found was between aluminum and flat brown paint, this being around 10 or 11 per cent.

Population as an Index to Electrical Development

BY N. B. HINSON[1]
Member, A. I. E. E.

IN making plans for the future in the electrical utility business it is necessary to make estimates of future growth. Various methods have been used. The usual method is to plot growth of one kind or another against time. This gives an upward curve which is difficult to project mathematically and usually is misleading if projected ahead more than two or three years in a rapidly growing territory. In the electrical utility field various values have been plotted against the number of consumers or meters. This is all right for past data but for the future the number of meters or consumers would have to be estimated and this would depend upon the increase in population, especially if all the present population now had service.

This led to the use of population as the abscissa rather than time or consumers with any of the values desired as ordinates. This gives a straight line for practically all present values and the future is a straight line projection with a simple formula. The lower end of the line does not usually cross both zero points and this fact gives the changing values per unit of population.

The various values at the very beginning of the industry do not give the correct trend as only a small number of people had service, but the business is now and has been for the last ten or fifteen years developing very uniformly and consistently and these later values give the correct past trend.

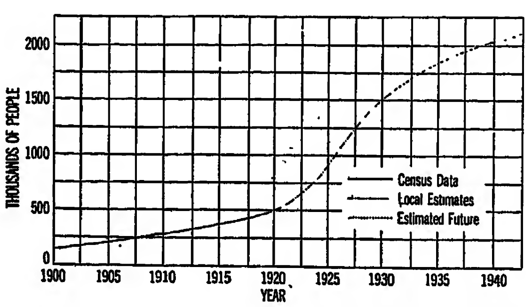

FIG. 1—POPULATION SERVED DIRECT BY SOUTHERN CALIFORNIA EDISON CO.

Population for the past, at least up to the last census date for any city, town, or county, is easy to obtain and in many locations accurate estimates up to 1928 are available. However, when it comes to projecting these values for ten or fifteen years into the future quite a problem arises, particularly in rapidly growing territory such as is found in numerous locations in the United States.

Raymond Pearl in his book, "Studies in Human Biology" has developed a theory of population growth which gives a curve of population for various cities and countries that describes past growth with great precision and fidelity, and predicts future growth in a more satisfactory manner than the usual method of projecting ahead with the same percentage increase as the place under consideration has had for a number

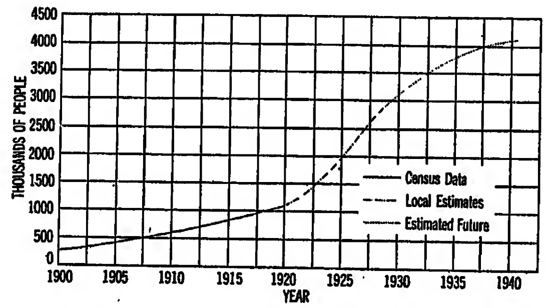

FIG. 2—TOTAL POPULATION SERVED BY SOUTHERN CALIFORNIA EDISON CO.—INCLUDING WHOLESALE

of years back. This type of curve Mr. Pearl calls the "Logistic" type curve though it has come to be known in our territory as the "Fly Curve" from one of the experiments he performed and describes in an article entitled the "Biology of Population Increase."

The population curves used for the territory which will be described were compiled from the census data for 1900, 1910, and 1920, and from estimated values of various Chambers of Commerce, Local and State Officials, Statistical Bureaus, etc., for the years 1921 to 1928. These curves were then projected ahead from the known data, the rate of growth, according to Mr. Pearl's conclusions, decreasing as the saturation point is approached. See Figs. 1 and 2.

The system on which these studies have been made is that of the Southern California Edison Company serving in Central and Southern California. Southern California, in which most of the small towns and cities are located, is one of the fastest growing communities in America. More than 99 per cent of all the houses in the territory covered have electric service and this value has been more than 90 per cent for ten years. Also the Southern California Edison Company supplies 62 per cent of the total kilowatt-hours direct to their own retail consumers, and 38 per cent wholesale to other companies and cities for redistribution and to the railways.

1. Southern California Edison Co., Los Angeles, Calif.

Presented at Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., September 3-6, 1929.

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In considering gross revenue, kilowatt-hours generated, and kilowatt peak, the total population in the territory served direct and indirect were used, and for horsepower connected, number of meters, and system betterment budget, the population served direct was used. These are illustrated in Figs. 3 and 4.

As will be seen, the population served is plotted uniformly and the date at which so many people were in the territory, or it is estimated from the population curve will be in the territory, is set opposite that number of people. The values of kilowatt-hours or horsepower or whatever is being plotted are set opposite the year in which they occurred. These points lie in such a position that in all cases a straight line can be drawn through the group, and this line projected ahead gives values for the future.

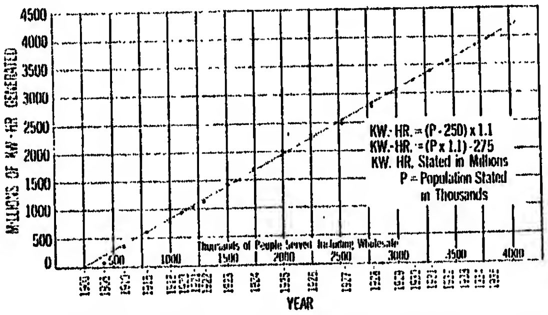

Fig. 3—Total Kw-Hr. Generated Yearly—Uniform Population

Since the values for the future are dependent on population which is an estimation, such future values for more than five years are liable to be in considerable error, but it supplies a means of getting values which can be calculated and is much better than projecting curves which are changing their shape from year to year. Figs. 5 and 6 illustrate the same data plotted against time. This will illustrate the difference in the two methods. Also as additional data are available such as the census for 1930, the population curve may change but it is only necessary to move the date to its correct position on the various studies. In other words, the straight line values are such that they show the value when there is a given number of people, irrespective of the date on which it occurs.

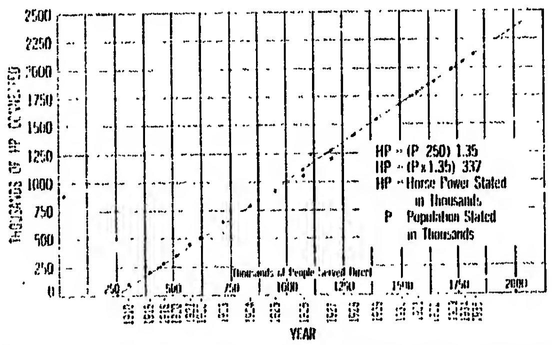

Fig. 4—Total Retail Hp. Connected—Uniform Population

The foregoing are all with regard to the system in general and assist in forecasting so far as generation and transmission are concerned. A study was made of the load on small stations supplying cities and towns so as to be able to forecast the transformer capacity necessary in the future, particularly when new stations are contemplated so as to install transformers that will not have to be changed within a year or two.

These studies were started on a load density basis of kv-a. per square mile. These studies were made on ninety cities and towns in Southern California, ranging from 1500 to 150,000 in population, the average being 10,000. The original study was made in 1925. This same study was made for the year 1928, using seventy cities which are incorporated, and on which it is possible to get a fairly accurate estimate at this time of population.

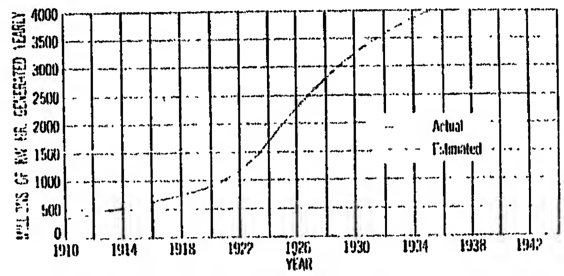

Fig. 5—Total Kw-Hr. Generated Yearly—Uniform Time

The maximum kv-a. demand for the year 1928 was used and the area in square miles of the developed territory, that is the territory actually built up including all vacant lots. This gave a value of kv-a. demand per square mile which varied from 270 to 2700. There seemed no logical relation between areas so the population for each city was taken and the cities grouped according to size, that is average values for all cities 1000 to 5000, 6000 to 10,000, 11,000 to 21,000, 21,000 to 30,000, 31,000 to 40,000, and 41,000 to 150,000, the last group including only five cities.

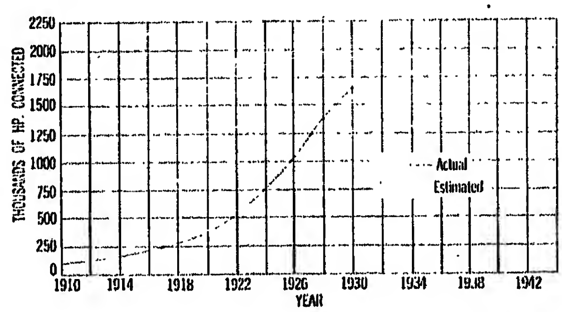

Fig. 6—Total Retail Hp. Connected—Uniform Time

The values of kv-a. per square mile for each group plotted against the average population for each group gave practically a straight line as shown on Fig. 7. Spotting all seventy of the cities shows how close they follow the average. This gives a simple formula for kv-a. per square mile for various sized cities and this

times the developed area in square miles gives the peak demand. This has been applied to several cities for which the data are available for five or ten years in the past and they check very satisfactorily. These apply only to a unit city; if two cities have combined and each had its own business district the combined city will give values of kv-a. per square mile that are too high, that is a city of 25,000 people developed as a unit has a greater load density per square mile than two cities each of 12,500 combined as one city. This system of future peak load projection has been used to set up the probable demand for all cities five years in the future. There has been some increase in the kv-a. demand per square mile during the last three years for any sized city so that it will be necessary to check these data again after the 1930 census. However, it gives a fairly accurate check on the probable future demands.

Fig. 8 shows the peak demand of the various cities plotted against the population. This value has been increasing yearly due to the increased use per capita of electric energy; it was 110 kv-a. per 1000 people in 1920, 125 in 1925, and 150 in 1928. For the smaller cities the peak demand is higher due to less diversity of load. This is also seen in the kv-a. per square mile being lower for the smaller cities as the development is not as uniform as the larger cities.

For making forecasts for the future no hard and fast rules will apply and all these means are used to check from as many angles as possible the future value. The

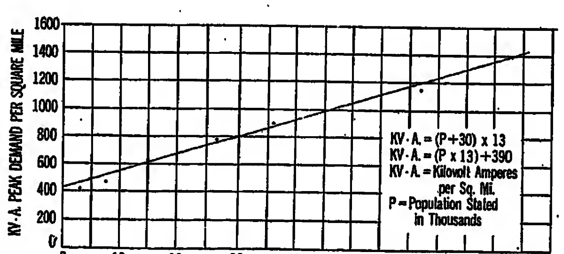

FIG. 7—KV-A. PEAK DEMAND PER SQUARE MILE—GROUP AVERAGES OF 70 CITIES

regular daily and monthly peak load readings on each station which have been kept for a number of years can be projected ahead as a check on future loads.

The distribution system is divided into thirty-two districts with an average of 13,000 customers, the minimum being 3000 and the maximum 50,000. Each of these districts has separate records and is set up similar to a small company. Any data that check up satisfactorily for all the districts may be used for the system. From these data yearly, average values of people per meter, per distribution transformer, per distribution transformer kv-a. rating, per pole, per mile of line, per substation, kv-a. capacity, per substation peak kv-a., per kw-hr. per year consumed can be determined. These values change from year to year but only slightly and these changes can be determined.

These data would not be the same in various parts of the country as the saturation is different and the character of the territory is different. Such values worked out for a particular territory enable fairly accurate estimates to be made of many of the factors entering into its electric utility business. In a territory in which practically every house has electrical service and has had for a period of approximately ten years, the various factors are perhaps more nearly related to the number of people in the city or territory.

This system of using population as a means of determining values of electrical development has been of

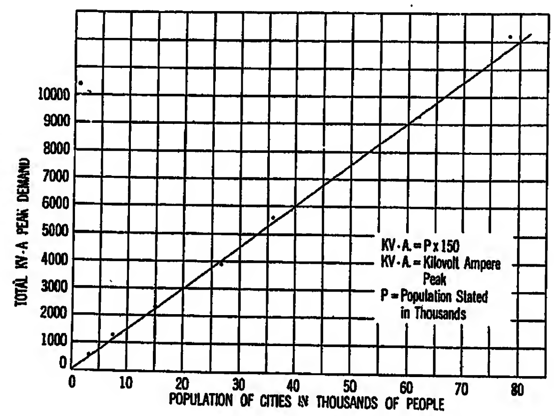

FIG. 8—TOTAL KV-A. PEAK DEMAND OF CITIES—GROUP AVERAGES OF 70 CITIES

great assistance in a rapidly growing territory and has enabled the mathematical determination of values in the future which otherwise would be pure guess work.

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Discussion

C. I. Anissimoff: I think Mr. Hinson has given an excellent paper; I object, however, to one expression he used, namely, "mathematical determination." I think, it is fortunate, it is not mathematical; it is determination "by sight," I should say, from the graphs. It could have been mathematical only if the complex phenomena involved were "idealized," which in our case means distorted, and the results would have little practical value, if any. The results of Mr. Hinson's method, however, can be used to advantage.

Also I want to ask a question. Ordinarily estimated future load is plotted against time; Mr. Hinson plots against population. I want to ask what is the advantage of changing the coordinates as Mr. Hinson did?

M. A. Lissman: Forecasters of population have made use of that branch of mathematics dealing with probability and statistics. While uninitiated people may hold the opinion that this branch of science is rather crude, I can assure them that the mathematical equipment desirable to deal with problems of population forecasting is of the highest order. At first glance, it appears paradoxical that in probability problems, provided the effect investigated is the result of numerous small independent causes, then the less we know about these causes the more satisfactory the treatment of the problem. In fact, if very large trends are apparent, then the effect of such known tendencies must be considered separately, because large known tendencies cannot be included in the statistical treatment.

N. B. Hinson: I might have gone into more detail regarding some of the methods of determining population. First of all, if you try to guess at the total population of a section of the state, and say there are so many people in Southern California without any further study, you are likely to be far from the real facts, but if you break the territory up into counties, cities, towns, rural communities, and analyze each of them, and then add them all together, you get a resulting population which is much more accurate than if you are guessing at the large section.

If we plot time against population, or time against any electrical values, we get a curve which is fairly flat in the early years but rises rapidly toward the end. In Southern California where we have had a rapid increase in population this upward trend is very pronounced. If you attempt to guess where it is going in the future you have quite a problem. Of course, you can say it is going to grow at the same rate of increase as during a certain period in the past. If you did this for this territory, using the last eight years as the index, in a very few years you would have an infinite increase in one year. From observing these you know that such an assumption is wrong, except for a short time in the future.

When you plot the same data against uniform population, with the date opposite the number of people in the territory at that time, you get practically a straight line. If you project this line ahead it is still correct for the particular number of people, though it may not be correct for the date which appears there. In other words, if you are talking about 3,000,000 people, and you have a certain value for 3,000,000 people, and a date, we will say 1930, if this number of people doesn't happen to arrive until 1932 all that is wrong is the date, so we just change the date. By that I mean, if you are making one of these projections, the thing you have to change, after you discover your population trend is different, is the date and you still have the value, stating that there will be so many kilowatt-hours for so many people.

The census data for 1910, and 1920, were used in these studies and we are looking forward to the 1930 census as another definite point on our population curve. We have also used the number of customers which we have connected year by year as a check on population growth. The yearly school attendance records give another check. There are numerous local bodies which have data on population and these are all used as checks on information obtained from other sources.

These various values are plotted together and if they all show the same trend, we have a good reason for assuming that the population curve is nearly correct. When they start to bend over you have a good idea that the population is not growing at the same rate as it did in the earlier period.

With regard to Mr. Anissimoff's question of the term "mathematically"—I meant only that if the data are correct, it is easy to determine the ratio between the two sets of data and to project it mathematically into the future.

Flames from Electric Arcs

BY J. SLEPIAN[1]
Fellow, A. I. E. E.

Synopsis.—*The origin of flames from arcs is considered. Their low dielectric strength is attributed to ionization, and their rate of recovery of normal dielectric strength is computed. The large influence of temperature is brought out. Computations are given and experiments described which show how flames can be reduced by passing the arc gases through narrow channels.*

Flames from Electric Arcs

It is well known that heavy current arcs in air such as occur in switches of usual construction give off large volumes of luminous gases or flames. These flames have a large volume in comparison to the arc itself which forms a core of comparatively small section, and it is quite certain that they have a much lower temperature and much lower electrical conductivity than the arc core itself.[2] Nevertheless these flames constitute one of the most troublesome features of switching in air in circuits of more than a few hundred volts, because they have a very small dielectric strength and will cause breakdown if they bridge live parts. This low dielectric strength persists for a relatively long time, and because of their large volume, considerable clear space must be provided in which these flames may dissipate themselves.

I. Origin of Flames

In general, these flames consist of gases which have passed through the arc core itself. The temperature of the arc core is more than 2500 deg. cent.[3] and hence the density of the air or gas there is one-ninth or less of the density of the air originally occupying the arc core space. The air displaced by the formation of the arc core will thus make up some of the flame, and if the flame temperature is more than 1000 deg. cent., will occupy a volume more than four times the volume of the arc core. This, however, will account for only a small portion of the arc flame.

The motion of the air in the neighborhood of the arc while it is playing, probably accounts for a great deal more of the flame. When the motion of the air is regular, (stream line motion) and such as does not tend to change the cross-sectional area of the core, the arc will merely move with the air, and little air will pass through the arc core itself. When, however, the motion of the air is such as to tend to increase the cross-sectional area of the core, and particularly when the air motion is turbulent, then a considerable volume of air will pass through the arc core. Such turbulent motion is to be expected from the magnetic reactions in a heavy current arc and when an arc is moved laterally very rapidly as in a magnetic blowout switch.

The gases and vapors given off by the electrodes will also contribute very largely to the flame. When the end products of the combustion of the electrode materials are gases, as in the case of carbon for example, the contribution of large volumes to the flame will be apparent; but also when the electrode vapors may be expected to condense to finely divided solids or liquids in the relatively cool flame, as in the case of copper and other metals, the projection of large volumes of vapor from the electrodes longitudinally into the arc will cause a turbulent motion which will bring large volumes of air through the arc core.

Flames will also result from gases which do not pass through the arc core, if the arc passes near a material which is decomposed by heat into an easily combustible gas. Thus if the inner faces of the arc chute of a switch are lined with fiber, paper, or similar material, a great increase in the volume of flame will result. In fuses of the expulsion type where the arc plays in a fiber tube, a large part of the flame is probably due to burning decomposition products of the fiber.

II. Low Dielectric Strength of Flames due to Ionization

The dielectric strength of the flames from arcs is astonishingly low. Many instances are known where the flames from arcs caused breakdown between parts having potential differences of less than one thousand volts, and separated by inches through the air. The normal breakdown between such electrodes would be 50,000 volts or more.

This very low dielectric strength indicates that the flames are in a state of considerable ionization, a conclusion which would be reached from their luminosity also. If the flames were only very slightly ionized, like ordinary air, we should expect a dielectric strength approximately proportional to their density, that is reduced from normal only three or four fold. The presence of ions in large numbers causes the field produced by an applied potential to be considerably distorted, so that the breakdown voltage is lowered very considerably, and made approximately independent of electrode separation. This is explained in the author's paper, *Extinction of an A-C. Arc,* (A. I. E. E. Quarterly Trans., Vol. 47, October 1928, p. 1398).

The flame gases which have passed through the arc

1. Consulting Research Engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

2. Hagenbach, "Der Elektrische Lichtbogen," *Leipzig,* 1924, p. 257.

3. *Ibid.*, p. 216.

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core are of course intensely ionized at the moment they leave the core. Recombination reduces the density of ionization very rapidly at first, but later the rate of recombination becomes much smaller so that ionization may persist for some little time.

The temperature of the flame gases very shortly after they leave the core is far too low to account for any ionization on a purely thermal basis, as may be seen by calculating from Saha's equation.[4] The only other obvious source of ionization is chemical effects such as arise in combustion flames.[5] Where there are combustible materials in the flame this ionization may persist for a long time, since the rate of combustion is limited by the rate of diffusion of oxygen into the flame which is a relatively slow process.

III. Dielectric Strength of an Ionized Gas

In the paper, *Extinction of an A-C. Arc,* referred to above, the following formula is derived for the breakdown voltage of ionized air.

$$V = 2.42 \times 10^{13} \times \left(\frac{273}{T + 273} \right)^2 \times \frac{1}{n} \quad (1)$$

Here V is the breakdown voltage, T is the absolute temperature, and n is the number of ion pairs per cm.^{3} of the gas. It will be noticed that the distance between the electrodes does not appear in the equation.

This equation, which must be regarded as only very approximate, was derived by considering conditions in the layer of air immediately adjacent to the cathode. On the application of voltage, this layer becomes at once denuded of electrons, and until breakdown occurs, bears practically the whole impressed voltage.[6] The thickness of this layer for a given impressed voltage was calculated on the hypothesis that the positive ions were relatively immovable in space, and breakdown was assumed to occur when the maximum gradient in this layer reached $30{,}000 \times \frac{273}{273 + T}$ volts per cm.

Actually, the positive ions do move, and their motion will cause the gradient in the cathode gas layer to be considerably less than calculated. Also the gradient for breakdown at lower voltages is much greater than $30{,}000 \times \frac{273}{273 + T}$ volts per cm. Equation (1) then can only be used to give very rough orders of magnitude. It can be very useful, however, in bringing out the strong influence of the temperature of the gas, and the value of any means for reducing the density of ionization of the gas.

4. *Phil. Mag.*, 40, 1920, p. 972.
5. *Handb. d. Physik*, Geiger & Scheel, Berlin, 1927, Vol. XIV, p. 190.
6. For detailed quantitative treatment of the physics of these deionized sheaths around electrodes in ionized gases see Langmuir & Mott Smith, *General Elec. Rev.*, Vol. XXVII, 1924, pp. 449, 538, 616, 762, 810.

IV. The Decay of Ionization in a Gas

Immediately after leaving the arc core, if the gases are not exposed to deionizing surfaces of solids, the density of ionization is practically entirely determined by the rate of recombination of the ions. This rate of recombination is proportional to the density of positive ions and also to the density of negative ions, so that we have[7]

$$-\frac{dn}{dt} = \alpha\, n^2 \quad (2)$$

If α, the recombination constant, was really constant in time Equation (2) could be readily integrated giving

$$\frac{1}{n} - \frac{1}{n_0} = \alpha\, t \quad (3)$$

n_0 being the initial density of ionization, and if n_0 is very large, as it is in the arc core itself, $\frac{1}{n_0}$ is negligible and Equation (3) becomes

$$n = \frac{1}{\alpha\, t} \quad (4)$$

Plimpton[8] has found that α for ions generated by X-rays shows an aging effect, being considerably smaller for older ions than for newly formed ones. This result may, however, be due to the non-uniform distribution of ions formed by X-rays. For air at normal pressure and temperature several investigators have found $\alpha = 1.6 \times 10^{-6}$ for "aged" ions. α is found to be greatly affected by the temperature, increasing very rapidly as the flame cools. Meager experimental data show that α varies inversely as the cube of the temperature. Equation (2) might then be better written

$$-\frac{dn}{dt} = \alpha\,(t, T)\, n^2 \quad (5)$$

showing explicitly the dependence of α upon the time t, and absolute temperature T.

However, since it is not the purpose of this paper to determine actual numerical values of the dielectric strength of arc flames, but merely to get orders of magnitude and to show the great influence of temperature, we shall work with the following assumptions:

1. We shall take the value of α for air at normal pressure and temperature to be 7.6×10^{-6}.

2. We shall assume that the flame gases, immediately upon leaving the arc core, take on the absolute temperature T, and keep that value of temperature thereafter. We shall assume that α varies inversely as the cube of the absolute temperature. Thus

$$\alpha = 7.6 \times 10^{-6} \times \left(\frac{273}{T + 273} \right)^3 \quad (6)$$

7. Townsend, "Electricity in Gases," *Oxford*, 1913, Chap. VI.
8. *Phil. Mag.*, (6), 25, 1913, p. 63.

V. The Dielectric Strength of Flames from Arcs

From the standpoint of the designer of switches, it is the dielectric strength of flames from arcs which is important, rather than their luminosity, temperature, or other properties. Where the ionization of the flames is almost entirely residual, or that is, where there is little combustible material in the flames, Equations (1), (4), and (6) above serve to determine the dielectric strength of the arc flame as a function of the flame temperature T and the time t, in the resultant equation

$$V = 1.84 \times 10^9 \left(\frac{273}{T + 273} \right)^5 t \qquad (7)$$

A few numerical values will best bring out the significance of Equation (7) and particularly the great influence of the temperature. Consider the dielectric strength of the flame 0.01 sec. after it has left the core of the arc, during which time it may have traveled several feet.

DIELECTRIC STRENGTH OF FLAME
0.01 Seconds after leaving arc

Temperature of gas	Density of ionization ion pairs/cm.²	Dielectric strength volts
2000°C	7.6×10^9	450
1500°C	3.6×10^9	1,610
1000°C	1.3×10^9	8,300
500°C	3.0×10^8	98,500
0°C	1.3×10^7	1,840,000

The advantage gained by cooling the flame gases, which is considered desirable instinctively by switch

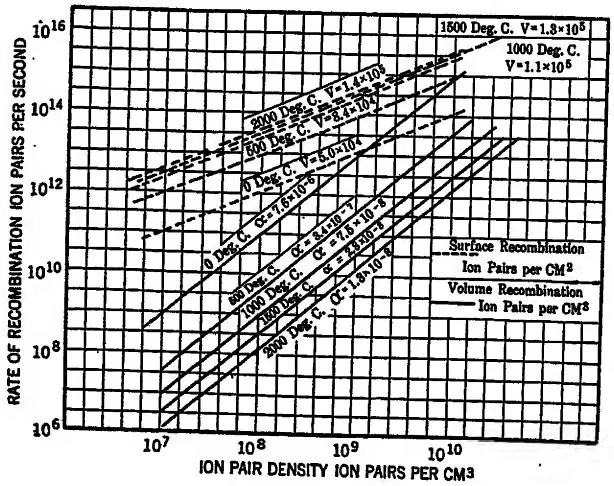

Fig. 1

designers, is forcibly brought out in the table. However, the direct instantaneous effect of lowering the flame temperature is only slight. The great increase in dielectric strength follows the lowered temperature shortly in time as a result of the large increase in the recombination rate of the ions in the cooler gas.

VI. Recombination of Ions at Surfaces of Solids

When an ionized gas is exposed to the surface of a solid, ions are lost by diffusing to the surface and being caught and recombining there. Under proper circumstances this loss of ions to surfaces of solids may far exceed the loss by recombination in the volume of the gas.

The rate of loss of ions to a surface will be given by

$$N = \frac{1}{4} n \nu \qquad (8)$$

where n is the density of ions in the gas adjacent to the surface, ν is the mean velocity of agitation of the ions, and N is the number of ions reaching the surface per

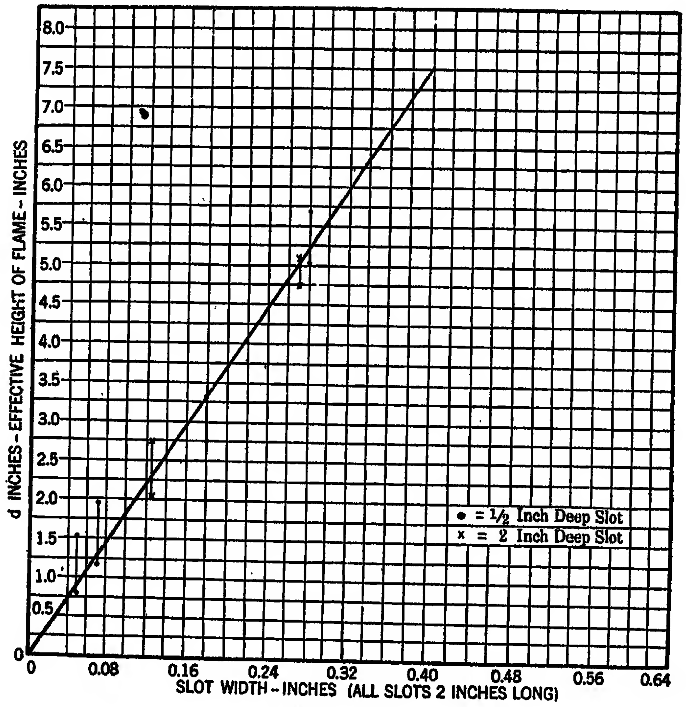

Fig. 2

cm.² per sec.[9] When the velocity of agitation of the ions of one sign exceeds that of the ions of the other sign, an electric field sets itself up at the surface which retards the faster ion, so it is the velocity of the slower ion which must be used in Equation (8).

The curves of Fig. 1 give a comparison of the recombination rates of ions at a surface with the recombination rates of ions in the volume of the gas for conditions which are of practical importance in the flames from switch arcs. We see that the recombination rate per cm.² of surface is 100 to 1,000,000 times as great as the recombination rate per cm.³ of the gas immediately adjoining.

If the gas is at rest relative to the surface, the layer of gas immediately adjacent to the surface becomes very quickly denuded of ions, and then ions which further reach the surface must diffuse through this layer of deionized gas. The surface then loses most of its deionizing efficacy. If, however, the gas is in rapid turbulent motion past the surface, fresh portions of the

9. Langmuir & Mott-Smith, *General Elec. Rev.*, XXVII, 1924, p. 450.

ionized gas are constantly exposed to the surface, and its deionizing activity is maintained.

VII. Experiments of C. L. Denault on Reduction of Flames from Arcs

The considerations given above of the influence of temperature and the deionizing effect of surfaces would lead one to expect that the flames from arcs would be greatly reduced in volume if the gases from the arcs were compelled to pass through narrow channels between solid walls. This is beautifully confirmed by

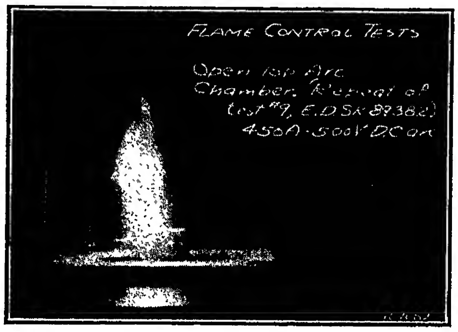

Fig. 3

experiments of C. L. Denault (which have not yet been published).

In these experiments an arc was formed by blowing a fuse in a soapstone chamber with an open top, 9/16 in. by 2-1/8 in. and 1-9/32 in. high. Covers were then placed over the chamber which compelled the escaping flame to pass through slots of various widths. A spark gap consisting of ½-in. diameter brass roads

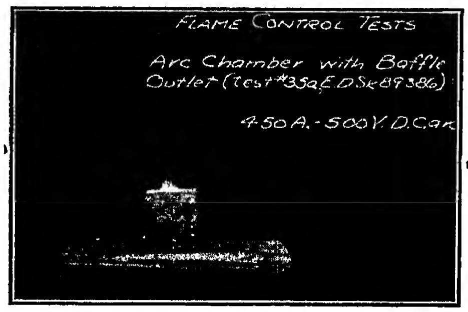

Fig. 4

with rounded ends, separated 0.9 in., and with 2200 volts 60 cycles impressed upon it, was used to determine the effective height of the flame, by determining what was the shortest distance above the vent at which the spark gap could be placed without breaking down. The breakdown voltage of the spark gap in normal air was 30,000 volts.

The curve of Fig. 2 and the photographs in Figs. 3 and 4, show the remarkable reduction in flame obtained by exposing the arc gases to deionizing surfaces.

VIII. The Deion Contactor

Recently contactor switches have been developed which use a weak blowout magnetic field and which extinguish the arc by means of a column of deionizing metal plates. These switches show an enormous reduction of flame in comparison with previous types of switches.

In the Deion contactor by the use of the deionizing

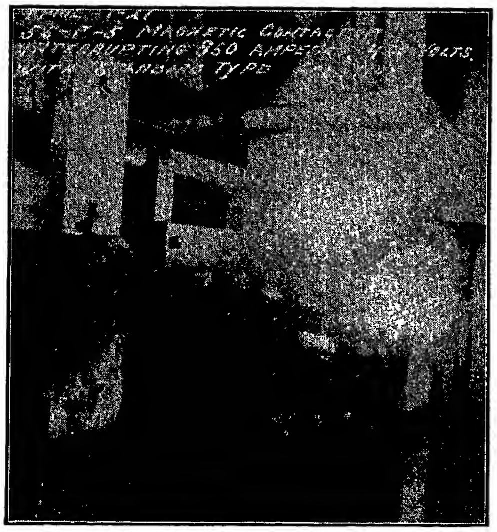

Fig. 5

plates the arc length has been considerably shortened, which in itself would cause a reduction in the total volume of arc flame. The arc is in a weaker magnetic field, which reduces the amount of air carried turbulently through the arc core, and therefore also the volume

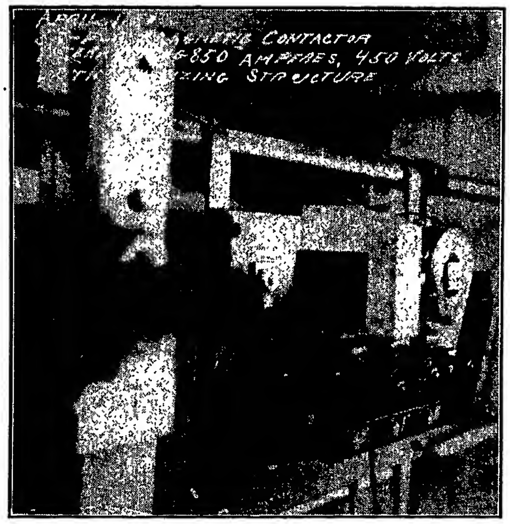

Fig. 6

of flame. Lastly, before escaping from the switch the flame gases pass through 1/16-in. channels between the deionizing plates where they are effectively cooled and deionized.

Figs. 5 and 6 show a comparison of the amount of flame emitted by a magnetic blowout contactor of the usual type, and a Deion contactor. The size of arc box is the same for the two switches, and the arc current is of the same magnitude. The absence of flame from the Deion contactor is quite remarkable.

Design Features that Make Large Turbine Generators Possible

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DEVELOPMENT in turbine generators has been so rapid during the past four or five years that any attempt to go into a detailed description of such development would involve too voluminous a work. The purpose of this paper, therefore, is to pick a few facts from a large experience of one manufacturer with the hope that these might be of interest to the profession in general.

In discussing the design features that may be incorporated in a turbine generator to give it high rating, the authors wish it to be understood that they do not subscribe to the carrying to an extreme of certain of the features. In fact, it is their idea that conservatism should be used in order to obtain the machine that will prove most satisfactory in service.

The electrical and the mechanical are so combined and interwoven that it is hardly possible to discuss each by itself but it may assist in understanding this subject to mention, first, the mechanical factors, and second, the electrical factors.

In 1924, the authors described some features in the building of a 62,500-kv-a., 1200-rev. per min. generator. Owing largely to economic consideration, the years since that date have seen the interest in machines of 1200 rev. per min. decline and the interest in machines of 1800 and 3600 rev. per min. increase at such a rate as to make it difficult for manufacturers to keep up with the ever increasing demand for larger and larger units.

62,500-Kv-a. Generator

During the year 1925, the company with which the authors are associated built and installed a 62,500-kv-a. generator, operating at 1800 rev. per min. As this generator constitutes a milestone in the progress of turbine generator development, it will be in order to give some of the factors which made possible the building of such a machine. The largest previous machines at this speed had a rating of 37,500 kv-a. These machines were ventilated by carrying part of the air to a chamber at the longitudinal center of the machine, from whence it flowed inwardly to the air gap where it joined the main body of air which had entered the air gap at the two ends, from whence it flowed outward through the remaining sections of punchings. This division of the air was adequate for 30,000-kw. machines. With machines requiring a length necessary for 50,000 or 60,000 kw., it was apparent that to force enough air through them, even though two paths were employed, would require pressures far beyond what would constitute good practise. The natural development, therefore, was to employ a larger number of multiple paths. The employment of a greater number of multiple paths removes the restriction from the air gap and places it in the air ducts themselves. Naturally if each alternate air duct were used as an inlet duct the air velocity through the ducts would be just twice as great as if all the ducts were outlet ducts. With higher velocities in these air ducts it became apparent that a real gain in efficiency could be made by improving the entrance conditions to these air ducts. The air as it enters the air gap has a direction parallel with the shaft. As soon as it passes within the restraining walls, formed by the armature and rotor surfaces, it is immediately acted upon by the rotating surface of the rotor and its direction quickly changed from an axial to a tangential flow. By means of specially designed vanes, which were inserted from the back of the punchings directly into the air gap, a complete study was made of the direction and velocities of the air in the air gap on actual machines under a wide varying ventilating arrangement. These experiments showed some rather surprising results as regards the resistance imposed on the air in passing from a tangential to a radial direction in entering the air ducts.

In order to obtain data, as regards the above feature, model sections of armature punchings were made up. These were tested in an air tunnel at pressures and velocities corresponding with those in the actual machine. A vast amount of data was collected on a large number of entrance ducts of many shapes. Some of these data showed that variations as great as 300 per cent were possible in the amount of air put through a given shape of air duct, and in a few cases it was even found that the air actually flowed into the air gap instead of outward as would be expected.

Fig. 1 shows a photograph of one of these models. It will be seen that the air duct which it is supposed to represent can be turned through an angle of 90 deg. By this means, it was possible to study the entrance condition to the various air ducts throughout the length of the machine and to determine their resistance to the flow of air over a wide variation of angular flow. In other words, the direction of flow of air in the air gap having been determined by measurement on an actual machine, it is possible by rotating the model into the correct angle to carefully measure the duct resistance to the flow of air from this angle.

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Fig. 2 shows the variations in the volume of air from one duct. The length of radial lines represents the volume of air passing through the duct at a fixed pressure for different angles.

Figs. 3 and 4 show the variations which exist in different designs of ducts. They represent the maximum and minimum flow under this study. These charts were made by putting a piece of paper over the ducts and marking out the outline and then recording the impact pressures at various points across the face of the ducts.

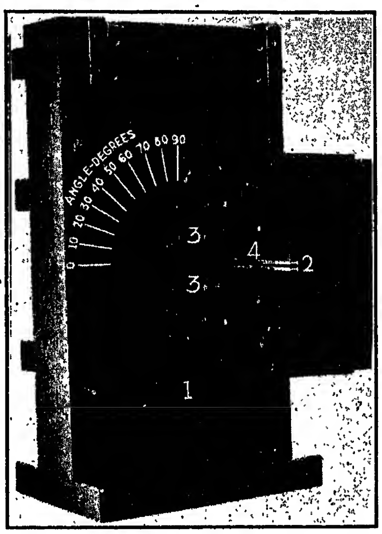

FIG. 1—STATOR VENTILATION MODEL

1. Air tunnel
2. One-half of adjustable block shown in position corresponding to peripheral air flow
3. Duct wedges of "air-slide" type
4. Stator inside space blocks

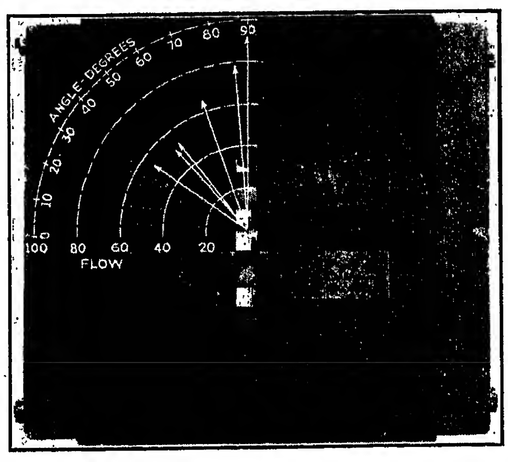

FIG. 2—STATOR VENTILATION MODEL

Showing wedge combination No. 17 completely assembled and ready for test. The radial arrows give the relative flow in the several positions

Armed with these data, the ventilating passages of the 62,500 kv-a. were laid out and it is gratifying to report that subsequent tests on the machine verified the earlier experimental results.

Fig. 5 shows results of test on this machine.

The net result of all this information when applied in the design of the 62,500-kv-a. generator was that this generator employing external blowers required practically the same amount of power to ventilate it as the 30,000 kw. previously built. When it is considered that 40 per cent of the loss on a turbine generator was formerly chargeable to windage, it will be seen that this saving in loss constituted a real step forward in the matter of efficiency. The outstanding facts which these experiments indicated, and which subsequent tests on the machine substantiated, was that as far as ventilation was concerned machines of any length could be built and if properly designed they could be as well ventilated as the shorter machines. This conclusion was of the greatest importance as it removed one of the factors which up to this time had more than any other impeded the progress in the size of generating units.

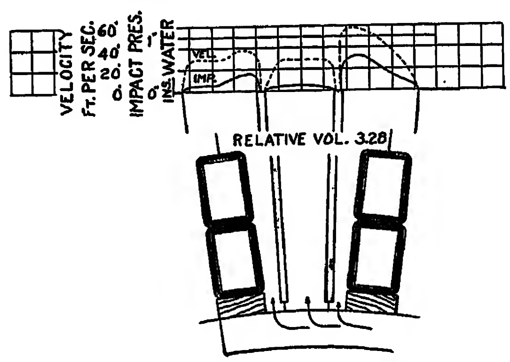

FIG. 3—AIR-FLOW CURVES

Minimum flow obtained—the best shaped retaining wedge; heavy lines—impact; dotted lines—velocity in the three passage ways between slots

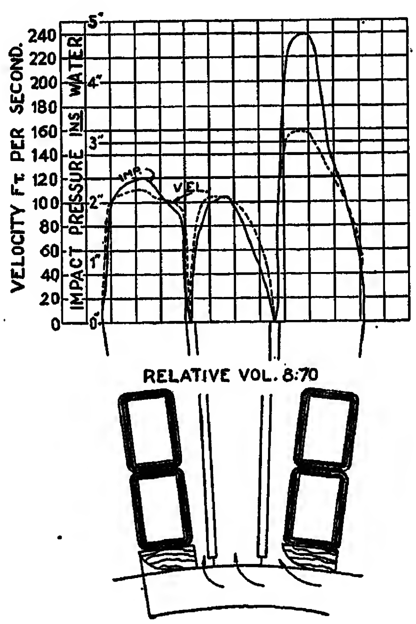

FIG. 4—AIR-FLOW CURVES

Maximum flow obtained—no retaining wedge across air duct; heavy lines—impact; dotted lines—velocity in the three passage ways between slots

Temperatures and Their Relation to the Size of Units

A few years ago it was thought by some designers, as well as users, that low temperatures were incompatible with large machines. The authors have never shared this view, and after a long experience are more strongly of the opinion that the larger the machine the more conservative the temperature should be.

Some of the largest single-shaft turbine generators built to date have temperature rises, by embedded detectors in the stator windings, of 45 deg. to 50 deg. cent. instead of 60 deg., and of 60 deg. to 70 deg. cent. in the rotor windings instead of 85 deg. cent. as permitted in the contracts. Such machines could be rated approximately 15 per cent higher and still have temperatures within the usual commercial guarantee in the United States for the largest turbine generators, or 25 per cent higher and still keep within the limit that is recognized as good practise for Class B insulation by the Standards of the A. I. E. E.

Most of the armature failures with which the authors are familiar, and which have occurred in recent years, have been the result of mechanical rather than electrical causes. A majority of such cases occurred before the general adoption of the closed ventilating systems of the present day, and were largely brought about by the stoppage of the ventilating passages by foreign substances. This in many cases caused the generation of gases in windings due to the temperatures getting beyond the boiling point of the constituents of the binding varnishes. These gases usually forced themselves along the length of the coil until the restraining influence of the slot walls allowed their escape. Once free of this restraint, they ruptured the insulation wall causing a failure. Still other failures were caused principally in the rotors by purely mechanical movements between the copper and iron, which movements cause an abrasion of the insulation to the point of failure. Either of these effects is greatly multipled when we come to core lengths such as are necessary in machines of 100,000 or 160,000 kw.

It has seemed best, therefore, to feel our way along in the matter of proper temperature rises for the extremely large turbo generators, at the same time putting forth every effort to minimize the serious consequences of expansions and contractions by introducing certain constructions in the windings themselves that will permit of expansions that will not be wholly longitudinal, and at the same time continue the improvements that have already been made in the quality of the varnishes or other cementing materials employed, in the hope of eventually obtaining insulations for high voltages that will be able to withstand much higher temperatures.

It can readily be seen that the quantity of insulating material is a factor in the temperature rises and that insulations should not be any thicker than what is required to give the dielectric strength needed for the

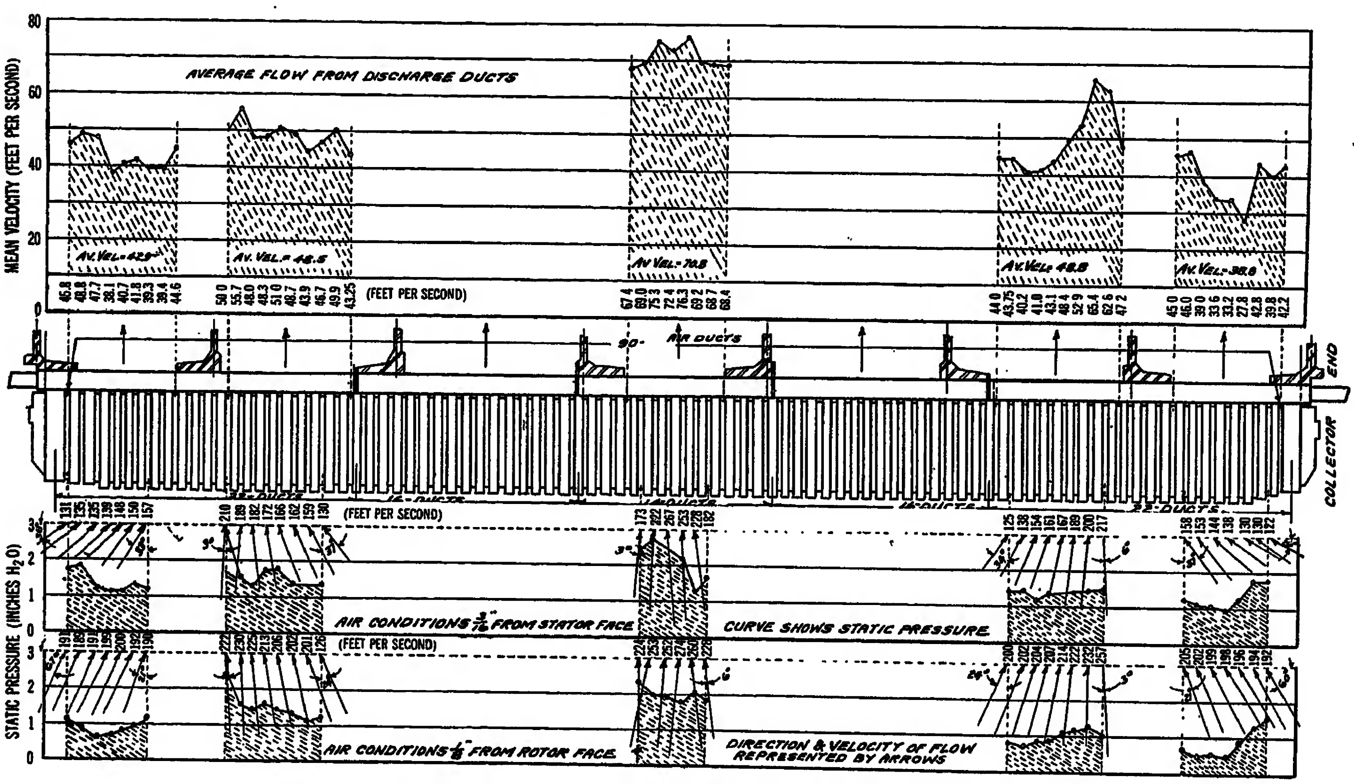

Fig. 5—Ventilation Tests on 62,500-Kv-A., 1800-Rev. per Min., 13,800-Volt Generator

Longitudinal cross section of stator core showing ingoing and outgoing sections: static pressures and relative directions and velocities of flow

highest potentials generated in service. The practise is now well established in the United States, as also abroad, of requiring insulations that will stand a high potential test for one minute of twice the rated potential plus 1000 volts. It is a question in the authors' minds as to whether such test is not too high and yet some designing engineers advocate higher tests, and a few engineers in the public utilities are inclined to call for still higher tests, apparently on the theory that the higher the test that insulation will stand the better the generator.

This attitude may be the result of the experience on earlier machines, where low potentials were the rule. Such machines if given sufficiently thick insulation to supply the proper space between copper and iron may have continued in service even when the dielectric value of the insulation was impaired to the point equivalent to that of air.

A one-minute high potential test should not be used as the sole criterion of a good insulation. The authors have witnessed tests on armature coils insulated for 13,200 volts which successfully withstood a one-minute high potential test of 100,000 volts. Such coils when subjected to potential of some 30,000 volts continuously failed after a short period.

The fact should not be lost sight of that the insulation surrounding a conductor serves a dual purpose. It restrains the voltage induced in the copper, and also acts as a conveyor of heat from the copper to iron. Its thickness, therefore, should be no greater than what will insure a resistance for years to such potentials as the windings are subjected.

Losses and Their Relation to Output

It is a much mooted question as to the relation that should exist in any given instance between the armature and the field magnetizations. High armature reaction becomes overpowering unless the designer by increasing the air gap maintains a ratio within such limits as he thinks will prove satisfactory in operation. The relation of field ampere turns at no load, normal voltage, to field ampere turns on short circuit with normal current is known as the short circuit ratio. Hence, a low short circuit ratio tends to a high rating for the speed under consideration and the physical dimensions of the machine. A few years ago it was the practise of the authors to design large turbo generators with a short circuit ratio of approximately unity but, in view of the designs of many of the European engineers where short circuit ratios not more than one-half as great exist, the tendency with us at present is to lower somewhat our former figure.

Machines of greater rating are possible when magnetic materials of the best quality are employed. It is important that careful studies be made of the magnetic densities that are permitted in order to obtain the lowest losses under load conditions. Any reduction in the fixed losses in the generator is of a two-fold benefit, for less air is required to provide the proper ventilation with lower power loss chargeable to the ventilation. For each kilowatt saved in these losses, approximately 0.25 kw. less power is required to ventilate such a machine.

Higher armature reactions or lower short circuit ratios result in an increase in the so-called load losses; at the same time they reduce other losses and result in cheaper machines. A proper balance then must be maintained between these factors so as to obtain machines of great reliability and long life.

With enormous amounts of power built into a single unit the desirability of building machines of great reliability cannot be overemphasized.

In a previous paper the authors made reference to investigations which were carried out in regard to losses existing in machines of this type with particular reference to those losses in the so-called inactive magnetic materials at the heads of machines. As a result of these and subsequent investigations the practise of using magnetic steels for such parts as the clamping fingers and flanges has been discontinued on all of these large machines, and non-magnetic materials substituted for them. The employment of these non-magnetic steels has resulted in a gratifying reduction in the losses. As a result of these and other improvements the efficiencies of these large units are of the order of 98 per cent instead of the 96.5 to 97 per cent which were the rule a few years ago.

One of the contributing factors in the trend toward larger units is the increased efficiency which such a unit brings. High efficiency, therefore, assumes an importance in these large units far beyond what it did in the units of years ago. The design factors for which the modern designer must strive in the order of their importance should be reliability, efficiency, and cost. If these factors are followed through to a logical conclusion, the size of units for a given output becomes greater than what would obtain if machines were designed to get the greatest output compatible with their temperature guarantees.

Due to their high rotational speed the frictional loss, commonly called windage loss, becomes a serious factor in the efficiency of this type of unit. The problem of operating this class of apparatus in a medium of low density has claimed the attention of engineers for years. With the advent of the closed system of ventilation and surface coolers for extracting the heat from the cooling medium, the problem of the utilization of a gas lighter than air received a marked impetus. Hydrogen cooling is a perfectly practical thing and its adoption will mark the next big step forward in the increase in efficiency of these large units. By employing H_2 cooling we may expect an increase in efficiency of some 0.6 per cent and some 25 per cent larger outputs from the same physical size of units.

High-Voltage Generators

Within the past few years interest has developed both in this country and abroad in generators built for volt-

ages higher than those which had been standard, namely 13,200–14,000 volts. This trend has been for entirely different reasons. In England voltages as high as 33,000 have been advocated and one machine has been built at this voltage. The justification for such a voltage lies solely in the elimination of the step-up transformers. In this country the trend toward higher voltages has been brought about largely by the increase in generator capacities, and in an effort to minimize switching difficulties.

The distribution areas being so widely scattered in this country, most of the power from the large stations to-day is sent out at potentials much higher than it would be possible with our present knowledge to build generators for. No attempt, therefore, has been made to adapt the generator voltage to the transmission potential. In those cases where power is distributed at various potentials, say 33,000, 66,000, and 132,000 volts, it usually works out cheaper to use step-up transformers for all three voltages than to wind the generator for 33 kv. and use step-up transformers for the two remaining voltages.

Still another difficulty in the design of generators for transmission potentials lies in the hazard involved in surge potentials to which such transmission lines, especially those of moderate potentials, are subjected. The class of insulation which it is desirable to use in the generator is not as well suited for resisting surge potentials as other classes which are totally unsuited mechanically to large generators.

All of these considerations have worked together to confine the building of large generators to the potentials which are most economical in station switching and bus bar equipment.

The introduction of the so-called double winding in large generators has retarded to some extent the trend to higher voltages in these machines. This double winding consists, briefly, in dividing the coils, which make up the three phases, into two circuits and arranging them in the correct slot relationship in such a manner that they will be in phase and voltage agreement with high self induction with respect to each other.

Each winding, therefore, will carry half the output of the machine. If these independent windings are tied to separate buses, the switching problem is greatly minimized as the current to be handled is just half of what would be the case in an ordinary generator or it would be the same as if the generator were wound for 27,600 instead of 13,800 volts.

Rotor

No description of generator development would be complete without some reference to the rotor as no part of these large generators has come in for such careful analysis and painstaking study as the revolving element. It is this element which must withstand all of the centrifugal strains, bending strains, and temperature strains due to heating and cooling and still maintain its alinement and balance so as to provide smooth operation.

There are three distinct types of rotors built by the leading manufacturers of to-day. The first is the solid rotor type in which the rotor is made up of one or more forgings. The second is the plate rotor type in which a series of plates or disks is bolted together to form the rotor body structure. The third is the through-shaft dovetail punching type, in which the shaft is a solid forging which has been slotted and dovetailed to receive the punchings which carry the rotor coils.

Each of these types has its advocates, and each type has some inherent advantages which the others do not possess. From time to time articles appear in the technical press of the world in which some author attempts to point out the superiority of one type over another. Such articles are distinctly all right as they tend to stimulate thought which leads to progress. The authors have no intention of joining in such a controversy. Their first-hand knowledge would allow them to speak with some authority on only two of the three types.

Suffice it to say that the manufacturing company with which the authors are associated has brought its steel forged type of rotor to its present state of perfection only after the most careful and painstaking research and that over one thousand of these rotors have been built and put into service and not one of them has failed due to imperfections in the rotor forging. This is an enviable record and is a most convincing argument that this type of rotor is thoroughly reliable if properly built.

In the design of the 62,500-kv-a. generator, described earlier in this article, the rotor diameter was the same as those of the 30,000 previously built. The centrifugal stresses, therefore, were no greater than had been previously encountered. With further increases in capacity of the units the diameters have been increased. Many of the stresses, however, on these rotors of greater diameter have not increased due to the fact that the copper space has not been increased in proportion to the increased diameter. The body stresses have increased somewhat but, to offset this, alloy steels are being employed which give a higher factor of safety than many of the smaller units enjoyed.

In the largest sizes the rotors are made of three pieces, a center cylinder and two stub ends, which carry the journals. There is a number of reasons for this construction; it reduces the size of the individual piece, and therefore the cost of such piece. It allows the main cylinder to be worked on its inner bore as well as its outside diameter, insuring better material, and it allows a more thorough inspection to be made of the forgings.

100,000-Kv-A., 16,500-Volt, 1500-Rev. per Min. Generator

Fig. 6 shows the 100,000-kv-a., 16,500-volt, 1500-rev. per min. generator installed in the Long Beach

Station of the Southern California Edison Co. This is the largest single turbine generator in operation in America. Its design brought up a number of problems largely mechanical, which are typical of the trend in modern design. When the order for this unit was placed, it was contemplated that the machine would be assembled at destination. The difficulty of transporting all of the component parts of a machine of this size 3000 miles across the country, and assembling them under conditions which are anything but ideal, made it seem desirable to design the machine so that it could be shipped completely assembled and wound. Weights were carefully scrutinized and it was finally decided that if the frame weight could be kept to 25,000 lb. the problem could be solved. Such a weight was out of the question on the basis of any past design. A design was finally worked out whereby both the weight and dimensional requirements for shipment could be met. The frame was divided into two parts, an inner member or cage (see Fig. 7) and an outer structure (see Fig. 8). The inner member consists of annular plates held on the outside by narrow steel slats, and on the inside by the core dovetail ribs which were let into the plate. This structure is intended largely as an assembling jig for the punchings. After the punchings were assembled and clamped the ribs and outside slats were welded in place. The whole structure thus became a rigid member which could be handled.

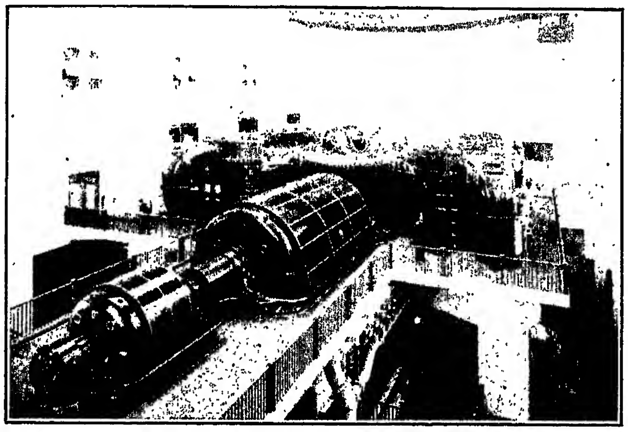

Fig. 6—100,000-Kv-a., 1500-Rev. per Min., 16,500-Volt, 50-Cycle Generator

With 4000-kw auxiliary generator and 94,000-kw. tandem compound turbine. Long Beach Station of So. California Edison Co.

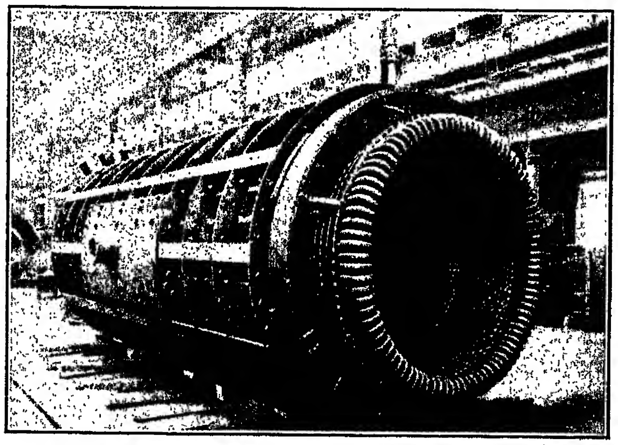

Fig. 7—100,000-Kv-a., 1500-Rev. per Min., 16,500-Volt, 50-Cycle Generator

View of inside stator structure complete with winding and supports. Turbine end

The outer structure consists of a number of foot plates spaced so as to coincide with the circular plates of the inner structure to which they are securely bolted when assembled on the base. These foot plates are welded to side plates which form an enclosure and add stiffness horizontally. Over this structure when assembled is placed a steel cover. This cover plate also carries radial supporting plates which form the various air chambers.

The strength of any structure is the strength of its weakest member. In the design it became apparent that the inner cage would be subjected to certain unusual stresses. It was found that no formula existed for calculating these stresses and a formula had to be developed. The calculations showed conservative stresses in this member. However, as there were available no data by which the correctness of the formula could be verified it was decided to test out the strength of the structure by means of a photo-elastic method. A celluloid model of one of the inner rings was made and loaded to simulate the body of the actual plates in the machine and the stresses determined. The stresses as determined by this method checked very closely with the calculated values.

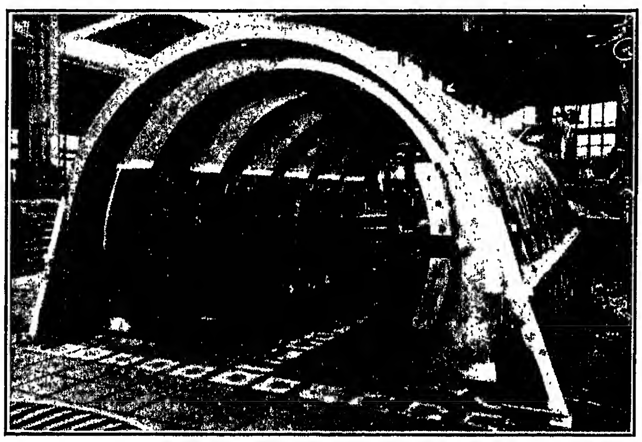

Fig. 8—100,000-Kv-A., 1500-Rev. per Min., 16,500-Volt, 50-Cycle Generator

View of outer stator frame shipped separately and bolted to inside structure at destination

160,000-Kw., 1500-Rev. per Min., 25-Cycle Generator

The use of 25-cycle power has practically given way to 60 cycles in this country except in certain districts, notably around Niagara Falls and the metropolitan

area of New York. While these latter places are considering the problem of changing over to 60 cycles, they still require large blocks of 25-cycle power.

Fig. 9 shows the frame with the ventilating housing and cooling casing for the 160,000-kw., 25-cycle,

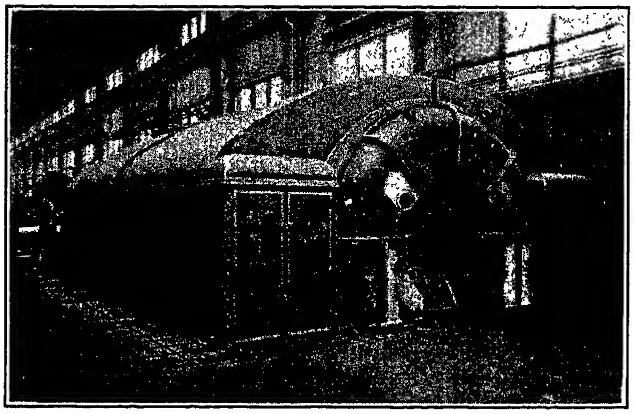

FIG. 9—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Ventilation housing containing the coolers

1500-rev. per min. generator for the New York Edison Company and installed in their 14th Street station. The building of a generator of this enormous capacity involved a number of new problems. The frame (see Fig. 10) is made entirely of steel plate welded and represents the most approved practise in this construction. The non-magnetic steel clamping flanges at the two ends of the stator and the cast iron end shields are the only castings in the generator proper. The employment of steel plate and the application of the art of welding has resulted in marked reduction in weight and at the same time resulted in a much stronger structure than was possible with fabricated cast iron structure formerly built. As an example of this weight reduction, a recent design of frame on a 75,000-kv-a. generator showed practically the same weight as the frame of a 37,500-kv-a. generator of an earlier design in which castings were employed. Owing to the physical dimensions of the 160,000-kw. generator and enormous weight, the stator of this unit was built at destination. Specially designed trunnions were necessary in order that the frame, after it had received its load of half a million pounds of laminations, could be turned from a vertical to a horizontal position on its base. See Fig. 10.

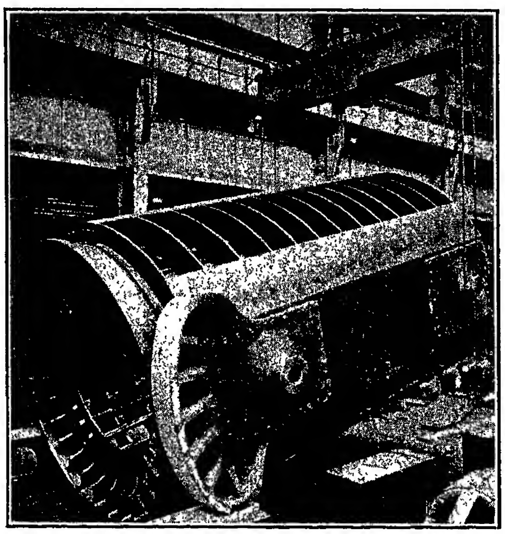

FIG. 10—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Showing stator frame and the special trunnion for changing after stacking core from vertical to horizontal position

The winding of this generator is of the transposed bar type with two bars assembled in each slot. This is the first machine to make use of the two circuit or so-called double winding. Each winding is connected delta and, to eliminate the objectionable harmonic currents in the delta, the pitch of the coils was made 66⅔ per cent. Each winding will be connected to a separate bus section and these buses will have no tie between them other than the generator windings. In case of a short circuit on one bus the generator windings act as a limiting reactor in reducing the flow of current along the bus.

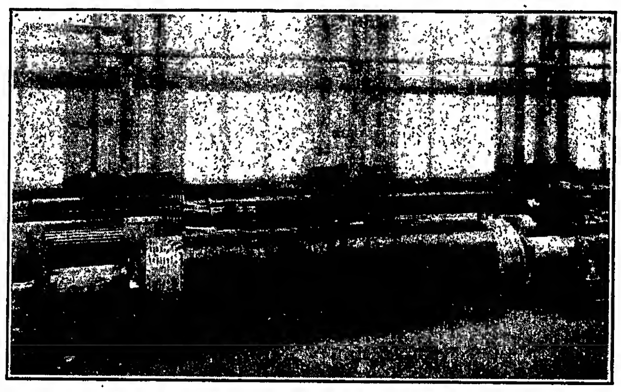

FIG. 11—160,000-KW., 1500-REV. PER MIN., 11,400-VOLT, 25-CYCLE GENERATOR

Wound rotor without end retaining rings showing aluminum saddles and blocking-in windings, length over-all 39 ft. 7 in., weight complete 290,000 lb.

Fig. 11 shows a view of rotor for the 160,000-kw. unit. The retaining rings are not assembled. The end construction of the rotor can be seen. The rotor forgings were made in three pieces, a body and two stub ends. The body portion alone weighed 228,000 lb. and is the largest single forging ever turned out by the steel mills. This forging involved the use of billet weighing 465,000 lb.

There is not contemplated at the present time, as far as the authors know, a turbo generator larger in capacity

than this unity power factor 160,000 kw. It may not be generally known to engineers other than designers that it is more difficult to design a 25-cycle machine of great capacity than it is to design a 50-cycle at the same speed, namely 1500 rev. per min. The amount of magnetic material is much greater for the lower periodicity and the extensions of the end windings of both stator and rotor beyond the magnetic cores are much greater. Hence, the authors have confidence that by the introduction of certain features discussed in this paper, such as hydrogen cooling, a 50-cycle generator conservative in its temperatures and other important characteristics could be designed and built at the present time for a rating of 200,000 kw. at 90 per cent power factor, or 222,222 kv-a.

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Discussion

L. J. Neuman: I should like to ask the question as to how the possibilities of ignition of the hydrogen are taken care of in this problem.

E. S. Henningsen: Designing a large turbine generator and making the outer structure explosion-proof seems to be impractical. That is, it is perfectly possible, but entirely uneconomic. Therefore, with such a machine there might be a possibility of an explosion.

With the synchronous condensers which we have built to date, because of their being much smaller machines, it has been possible to utilize the frame as an explosion-proof steel case. However, I believe the dangers of explosion from hydrogen are practically nil. The control of the gas in the frame of the machine can easily be arranged so that there will always be some positive pressure. Any leakage will be outward and there will be very, very little danger of air getting inside the machine to form an explosive mixture.

The second thing that makes me think the danger isn't very great is that there isn't much energy involved in the hydrogen inside of one of these machines and the explosive force is over so very quickly that even if it did explode, my opinion is it would simply open up a seam and it wouldn't blow off a piece of the machine.

One thing of interest in considering the dangers of an explosion, is that a great many manufacturing plants have hydrogen-filled furnaces for various kinds of work. At Schenectady, we have some large furnaces that are used for brazing pieces of steel together in an atmosphere of hydrogen. Those furnaces have been in constant use for many years right in the shop building with employees all around and we have never had an accident.

Effect of Surges on Transformer Windings

BY J. K. HODNETTE[1]
Associate, A. I. E. E.

Synopsis:—A study has been made of the reaction of transformer windings in grounded neutral systems when subjected to transient voltage surges such as exist on normally insulated lines. Measurements of the voltage distribution throughout the windings between various elements and to ground were effected by means of a cold cathode type cathode ray oscillograph and sphere spark-gaps.

An estimate of the stresses occurring in transformers due to the voltages occurring on transmission systems is made, basing them on the most recent data obtainable. The data indicate that the worst stresses, both within the winding and to ground, are in the vicinity of the line coil.

* * * * *

I. Introduction

With the rapid growth of transmission systems and their interconnection into larger systems, continuity of service is becoming increasingly more important. This has prompted a great amount of study on the subject of increased reliability of all component parts making up the system. Such studies have been conducted on transmission lines and connected apparatus. The power transformer constitutes a vital link in such systems. These transformers have shown an excellent record, undoubtedly due to the unceasing research and study conducted during their rapid growth in size and voltage in the past few years.

Transient voltage surges have long been recognized as one of the chief sources of trouble. During the past five years the klydonograph has yielded much information on the magnitude and frequency of occurrence of these surges on transmission systems under service conditions. More recently the cathode ray oscillograph has been perfected, making it possible to record accurately voltage-time relationships occurring in a small fraction of a second. By means of this instrument it has been possible to obtain actual photographs of surges.

The voltage surges occurring on transmission systems, and of necessity those with which we are concerned as affecting transformers, can be divided into three general classes according to their origin, namely, arcing grounds, switching surges, and electrostatic or lightning surges. It is the purpose of this paper to analyze various types of these surges and afford a common basis of studying their effects, particularly on grounded neutral systems.

Relative Importance of Arcing Grounds, Switching Surges, and Lightning Surges. Arcing grounds are discharges to ground usually from one phase or line of a transmission system. In case the neutral of the system is grounded the maximum voltage developed would be approximately 2½ times the normal voltage to neutral. For an isolated neutral system the maximum voltage may be as great as six times normal.

When a switch is opened or closed, energizing or deenergizing a circuit, a transient condition of voltage and current exists. The voltage during this process may reach values above normal as determined by the circuit conditions.

Reviewing the literature[2] on this subject we find the data obtained on a number of systems covering the whole operating range of transmission line voltages indicates that approximately 50 per cent of switching operations cause no appreciable voltage surge. Of the remainder 81 per cent are less than twice normal, 93 per cent less than three times normal, and 99.2 per cent less than 4.5 times normal. That is, only one switching operation in 250 causes voltages in excess of 4.5 times normal. The maximum voltage recorded on any system was six times normal and that was caused by deenergizing a line.

As a rule switching surges do not cause flashover of the line insulation. They must of necessity be short in duration in order to obtain excessive values and may rise to a maximum in the order of a few microseconds. Lightning surges on the other hand attain values of many times normal line voltages. In many of the cases recorded by the klydonograph, flashover of the line insulation is known to have occurred. The magnitude of the voltage, by virtue of the fact that the line insulation was flashed over, is much greater than for arcing grounds or switching surges. In Fig. 1 is shown a comparison of the voltages to be expected from the several sources together with the normal voltages of the system, the transformer test voltages, and the 60-cycle dry flashovers of normally insulated lines. It may be seen from this that surges produced by lightning are of most serious consequence and may be as great as 14 times normal for very short surges with lower values for surges of longer duration.

This does not mean that arcing grounds and switching surges are of no importance. Operating experience, however, indicates that they are not a common source of trouble with modern designs of transformers.

Shape of Lightning Surges. Much information has been contributed on the formation of lightning surges on transmission lines by Peek, Fortescue, Simpson, Cox, and others. It is generally accepted that induced voltages from lightning discharges are relatively low in magnitude and steepness, whereas surges produced by direct strokes may have abrupt fronts and be high in magnitude.

Factors Limiting Lightning Surge Voltages. The

1. Engineer, Westinghouse Electric & Mfg. Co., Sharon, Pa.
2. See Bibliography.

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principal factor limiting the voltage on a transmission line is the spark-over of the line insulation. The flashover of a string of insulators depends both upon the magnitude and the shape of the impressed surge and in the case of lightning surges is always greater than the 60-cycle flashover voltage. We may assume that failure commences as the 60-cycle spark-over voltage is approached and that spark-over is a function of time and the voltage above this value. The tail of the surge

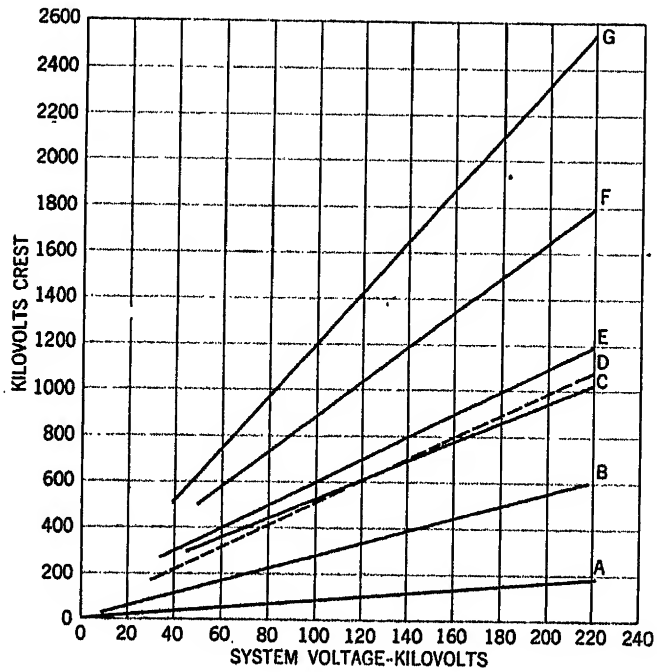

FIG. 1—COMPARISON OF SURGE VOLTAGES AND TRANSFORMER AND TRANSMISSION LINE INSULATION VOLTAGES (ESTIMATED)

A. Normal voltage of transformer (line to neutral)
B. Transformer test voltage
C. 60-cycle dry flashover of normally insulated transmission line
D. Probable maximum switching surges
E. Probable maximum voltage for 60-microsecond surge not causing flashover
F. Probable maximum voltage for 5-microsecond surge not causing flashover
G. Probable maximum lightning voltage possible (flashover on rise)

as well as the front affects spark-over and the more abrupt each is, the higher the voltage necessary to produce arc-over will be.

A rate of rise of 4000 to 5000 kv. per microsecond is probably about as rapid as would be expected for natural lightning surges. From experimental data for the flashover of line insulators, it is estimated that the maximum voltage which could exist on a line as a result of a direct stroke would be in the neighborhood of 2.5 to 2.7 times the 60-cycle crest sparkover. The curve for the probable maximum voltage, curve *G*, Fig. 1, is based on this computation. Points of this curve agree approximately with the maximum voltages recorded by the klydonograph.

Similarly, curves *E* and *F* for surges rising to maximum in less than a microsecond and decreasing to half-value in five and 60 microseconds respectively are drawn. These curves represent the approximate maximum voltages which can be propagated without causing sparkover.

In this connection reduced line insulation, ground wires, protective gaps, and lightning arresters should be mentioned. Each tends to limit the voltage on the system, particularly lightning arresters.

The second factor limiting the potential surges on apparatus is attenuation. It has been shown that where the voltage of the surge is very high the attenuation is very great. An example of this is in the attenuation of a surge of 1740 kv. to about half-value in a space of four miles. To this property of traveling waves much protection to connected apparatus is due.

II. GENERAL CONSIDERATIONS

When a steep wave traveling along a transmission line strikes a transformer it proceeds along the conductor of the first turn or turns in much the same manner as along the line.

As soon as a potential is established on the first turn of the entrance coil it sets up an electrostatic field enveloping the total space between it and ground. Each element of the winding thereby will acquire a potential depending upon its position in the field. As the wave penetrates further into the coil the electrostatic field changes every instant and with it the potential of the various elements.

Thus, a transformer reacts to an abrupt front wave during the time in which the wave is restricted to the first element much the same as a chain of condensers,

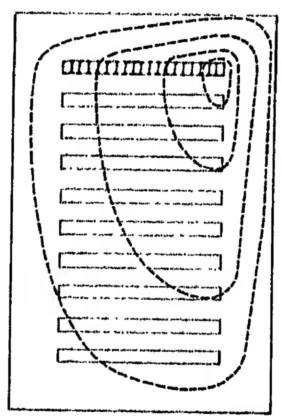

FIG. 2—SKETCH SHOWING ELECTROSTATIC DISTRIBUTION OF VOLTAGE WITHIN A WINDING DUE TO A STEEP IMPULSE ON THE FIRST TURN

Fig. 3A. *Cc* represents the capacitance between elements of the winding and *Cg* the capacitance to ground. The distribution of voltage to ground through the capacitances can be expressed as follows:

$$E = Eo \frac{\sinh n \sqrt{\dfrac{Cg}{Cc}}}{\sinh N \sqrt{\dfrac{Cg}{Cc}}}$$

Where E is the voltage above ground of any elements n, Eo is the voltage above ground of the first element, and N is the total number of elements involved.

A typical curve for the initial or electrostatic distribution in a transformer winding is shown in Fig. 4A. Each element of the winding includes an elementary portion

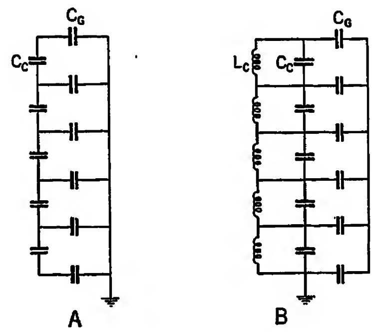

FIG. 3—EQUIVALENT CIRCUIT OF A TRANSFORMER

A. Equivalent circuit at instant of impact of steep wave
B. Complete equivalent circuit

of the total inductance of the winding. In order to completely represent the transformer winding schematically these inductances should be connected in parallel with the coil capacitance Cc, as shown in Fig. 3B. As time progresses a current will be established through the inductance and there will be a redistribution of the electrostatic energy between each of the elements and throughout the winding as a whole. This redistribution of energy will take place in the form of oscillations about the final steady-state distribution, which in the case of a transformer would be a straight line. If the incoming wave is maintained at a constant value long enough, the voltage in oscillating will rise above the steady-state distribution curve to a value almost as large as its initial displacement below it. (Fig. 4C.) These oscillations will be rapidly damped out by the losses in the transformer and the division of voltage reduced to the uniform distribution curve.

On the other hand, if the surge is not maintained but decays rapidly the axis of oscillation decays correspondingly and the magnitude of the oscillation is greatly reduced. To illustrate this, if the rate of decay were infinite there would be no time for the fundamental oscillation about any axis above the zero axis, and the original electrostatic distribution would generally represent the maximum voltages to ground. As the rate of decay decreases the magnitude of the oscillation would increase and a wave maintaining a constant value for one-half cycle of the natural period of the transformer would represent the other extreme.

Considering again the electrostatic distribution of voltage, the elements of the winding may either refer to the successive turns of a coil or to the various coils which make up the winding. In the case of the former, the several turns are insulated with a mass of insulation having a relatively high permittivity and are coupled closely together compared to their disposition to ground or other coils. Therefore the ratio $\sqrt{\frac{Cg}{Cc}}$ is low and the voltage gradient is correspondingly low. Extending the condenser chain beyond the first coil, assuming the first two coils connected together at the starts, introduces a voltage distortion from that represented by the equation (see Fig. 2). Since the end turns of the second coil are in close proximity to the line turn they receive a voltage from it as determined by the capacitance chain extending across the coil stack. A distribution of voltage across the second coil in opposition to the extension of the first is established and the two overlap. The distribution across the first coil should then be considered more correctly as a unit wherein the capacity of the last turn to ground is considered a series capacitance. This capacitance is relatively small and a high-voltage drop will result as compared to the adjacent turns.

Thus the voltage to ground decreases from the entrance turn across the first coil and increases from the start of the second coil. This effect extends into the

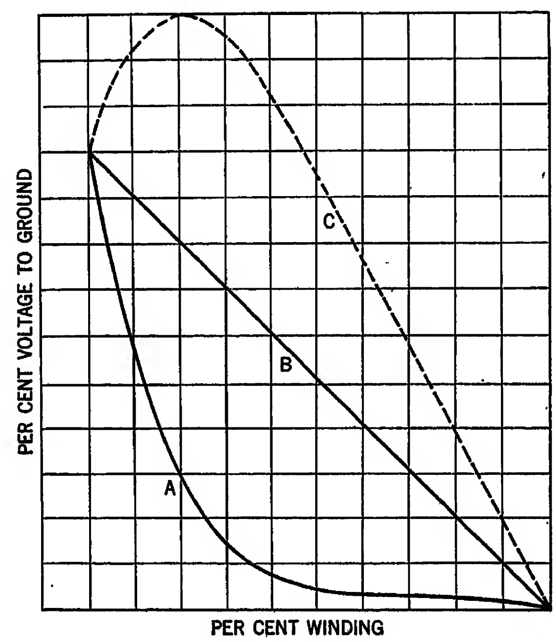

FIG. 4—INITIAL VOLTAGE DISTRIBUTION AND MAXIMUM POSSIBLE OSCILLATION PRODUCED BY A TRAVELING WAVE (ESTIMATED)

A. Initial or static voltage distribution
B. Final or 60-cycle distribution
C. Maximum possible voltage to ground by oscillation

winding but with less difference in potential across the coils the further they are removed from the entrance coil.

The distribution of voltage across the coil stacks follows in the same manner except that a compensation is necessary wherever the ends of two adjacent coils are connected together. If the coil stack is broken up by the interposition of other windings or reentries having a relation to earth much lower than the winding

considered, the effect will be the same as connecting a large capacitance to ground at that point in the capacitance chain. This means that in the electrostatic distribution, almost all of the voltage will be present in the line group. On the other hand, during the time of oscillation the increased capacitance requires a larger charging current which tends to retard the oscillation or increase its period.

From the above consideration it may be concluded that by properly proportioning the constants of the transformer it is possible to alter the static distribution

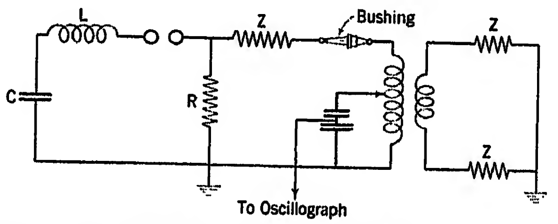

FIG. 5—SCHEMATIC DIAGRAM OF TESTING CIRCUIT

of voltage in the windings. For a given output capacity, the mass of the windings of a transformer is a constant within certain limits. Thus, if the coils are made narrow and of few turns the length of the winding must be long, and if the coils are wide and of many turns the coils will be few in number and the stack short. In the first case, the capacitance between coils will be relatively less than for the larger coils, whereas the capacitance of each to ground will not be greatly altered except near the ends of the winding or groups. As may be seen from this, the static distribution curve will be displaced much more from the uniform axis with a large number of narrow coils than with a few wide ones.

In proportioning the design of a transformer, consideration must be given to the space distribution as well as the turn-to-turn distribution of the voltage. In so doing the relative strength of the insulation to lightning voltage in the space should be given due weight. The amount of solid insulation used, its characteristics and the characteristics of the surrounding media, and the length of the path are factors in determining the lightning breakdown strength of insulation.

III. EXPERIMENTAL RESULTS

The circuit used in conducting these tests is shown in Fig. 5. The capacitance C was charged from an alternating source by means of kenotron rectifiers and discharged through an inductance L and resistance R. The potential drop across the resistance was impressed upon the transformer terminal. A lumped impedance Zs of approximately 500 ohms was connected between the transformer terminal and the source of voltage supply. The terminals of the secondary winding were connected to ground through similar impedances.

Waves rising to a maximum in less than a microsecond and decaying to one-half value in 5 and 60 microseconds were considered representative of fairly short and long lightning surges and these together with waves chopped while rising were used principally in this investigation. Waves of approximately 5- and 30-microsecond fronts were also used.

When the capacitance was charged to the required amount the surge was initiated by means of a three-way gap interconnected with the supply for the cathode of the cathode ray oscillograph. This provided the means for synchronizing the surge and the oscillograph. The voltage plates of the oscillograph were connected to various points in the winding through an electrostatic potentiometer. The maximum potential of these points was checked by a sphere spark-gap.

The effect of surges on the windings of the following transformers was studied in the course of this investigation.

3000-kv-a., 140,000- to 5000-volt single-phase, shell type transformer with the high-voltage winding divided into three groups.

667-kv-a., 66,000- to 7200-volt core type transformer with cylindrical low-voltage coils and circular pancake high-voltage coils. The winding was arranged on two legs with a reentry in the middle of each leg.

Both transformers were equipped with condenser type bushings.

The Effect of Varying Steepness of Wave Fronts on the

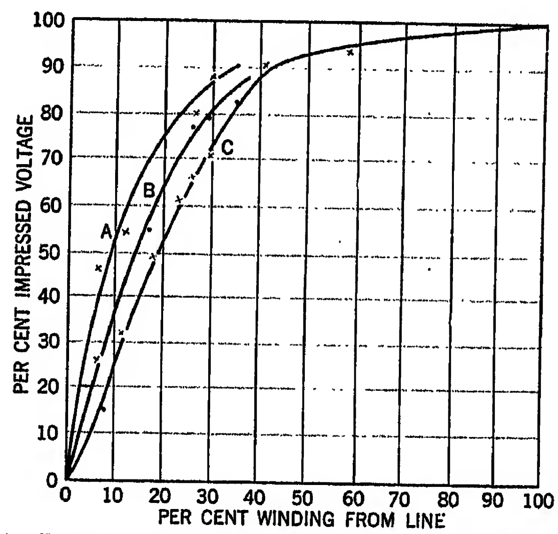

FIG. 6—DISTRIBUTION OF VOLTAGE IN WINDING AS MEASURED FROM LINE END (3000-KV-A. TRANSFORMER)

A. Surge with one-quarter-microsecond front
B. Surge with five-microsecond front
C. Surge with 30-microsecond front

Initial Distribution of Voltage in Windings. The curves in Fig. 6 show the distribution of voltage in the winding for waves of different fronts. In obtaining these curves the voltage was measured from the entrance terminal to various points within the winding. In the portion of the winding near the entrance, this approaches the initial or electrostatic distribution, since subsequent changes tend to make the voltage divide uniformly or the difference in voltage less. The fronts of the waves then are effective in establishing this relation and the longer the fronts the nearer uniform the voltage will divide.

This process was not carried to the limit but a uniform division would be expected after the front was of the order of a period of the fundamental.

The length of the tail of the waves has little effect on this curve as confirmed by measurements made with surges decaying to half value in 5 and 60 microseconds.

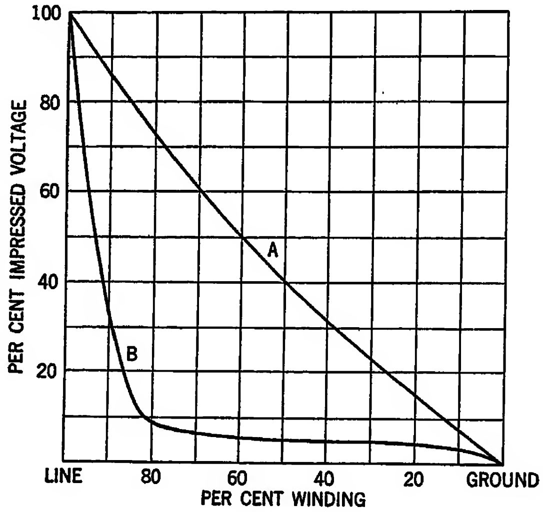

FIG. 7—COMPARISON OF VOLTAGE DISTRIBUTION IN LONG AND SHORT STACKS OF COILS

A. Short stack of wide coils
B. Long stack of narrow coils

The Effect of the Proportions of Winding on the Distribution of Voltage. Fig. 7 illustrates the difference in the voltage to ground in a short stack of wide coils

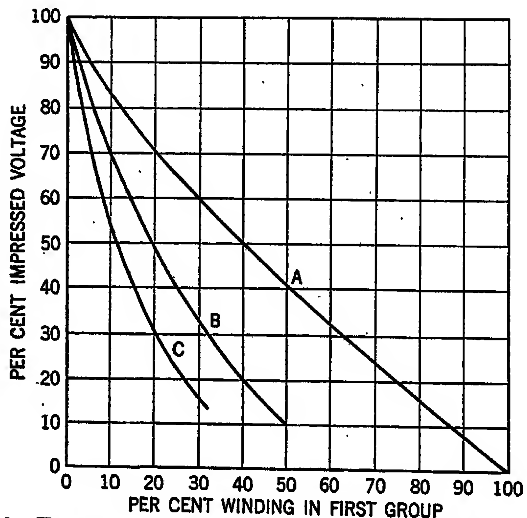

FIG. 8—THE EFFECT OF INTERLEAVED WINDINGS ON THE VOLTAGE DISTRIBUTION

A. Voltage distribution with one group
B. Voltage distribution with two groups
C. Voltage distribution with three groups

and a long stack of narrow coils when subjected to a five-microsecond surge. These values, as will be shown later, represent approximately the initial voltage distribution and are indicative of the worst stresses occurring in the stacks. Curve *A* represents what occurs in the line group of a well proportioned wide stack of coils and Curve *B* represents what occurs in a narrow stack of coils when short steep waves are impressed upon them.

When the windings are interleaved or broken up into groups the line group absorbs most of the surge voltage. Data were taken on the 3000-kv-a. transformer first by impressing a surge across the total winding, then across two groups, and finally across a single group of the winding. A five-microsecond surge was used and measurements of voltage were made to ground. Referring to Fig. 8, the three curves are seen to be of similar shape, or the distribution of voltage in the line group is practically unchanged by varying the number of groups. The discontinuous points in the curves indicate the

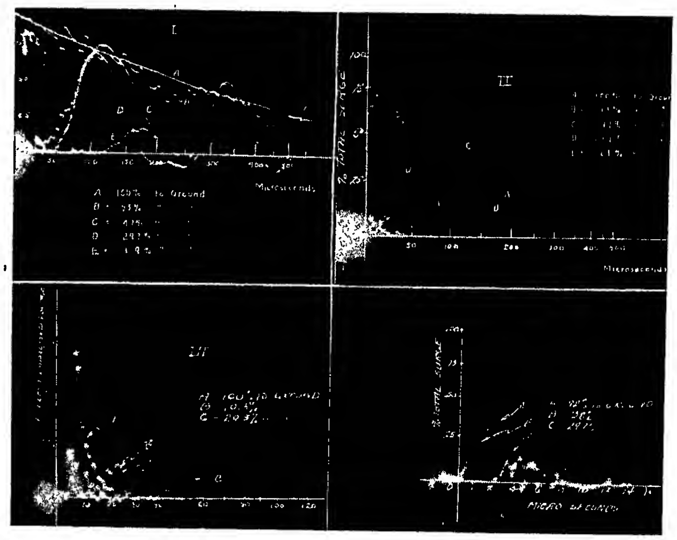

FIG. 9—OSCILLOGRAMS SHOWING VARIATION IN INTERNAL OSCILLATIONS OF 3000-KV-A. TRANSFORMER WITH DIFFERENT LENGTH SURGES

1. Very long surge, 250 microseconds to half value
2. Long surge, 60 microseconds to half value
3. Short surge, 5 microseconds to half value
4. Chopped surge

division of voltage across the group. The decrease in this value with the number of groups is not rapid. As shown, approximately 91 per cent of the voltage drop will occur in the first group where two groups are used and 85 per cent where three groups are used.

Internal Oscillations and Voltage to Ground. When a steep front surge strikes a transformer, oscillations are set up in the winding. The values attained by these oscillations depend largely upon the shape of the surge. Referring to the oscillograms, Fig. 9, the oscillations are seen to be higher for the longer tail waves. A point in the winding 29.7 per cent above ground reaches a maximum value of approximately 75 per cent of the total applied voltage for the extremely long wave, approximately 47 per cent for the long or 60-microsecond wave, 10 per cent for the short or 5-microsecond wave, and 5 per cent for the chopped wave. These

measurements were checked with the sphere-gap within reasonable accuracy.

Thus it may be seen that if the surge is sufficiently short, the voltage by oscillation does not rise above the initial voltage acquired from the front of the wave. This

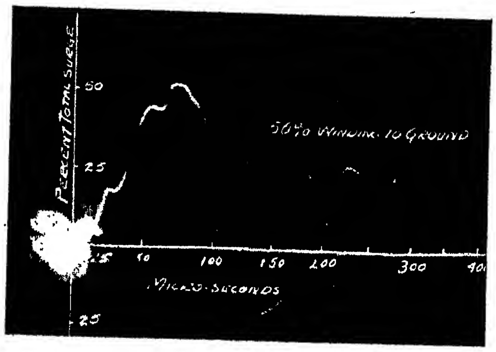

FIG. 10—VOLTAGE AT MID-POINT OF WINDING OF 667-KV-A. CORE TYPE TRANSFORMER PRODUCED BY A 60-MICROSECOND SURGE

condition is seen to be fulfilled by the five-microsecond surge in the case of the 3000-kv-a. transformer and a measurement of the maximum voltage to ground would also be approximately a measure of the initial voltage. On the other hand a measurement of the voltage above ground for longer waves would indicate the maximum values reached by oscillation. This is confirmed by

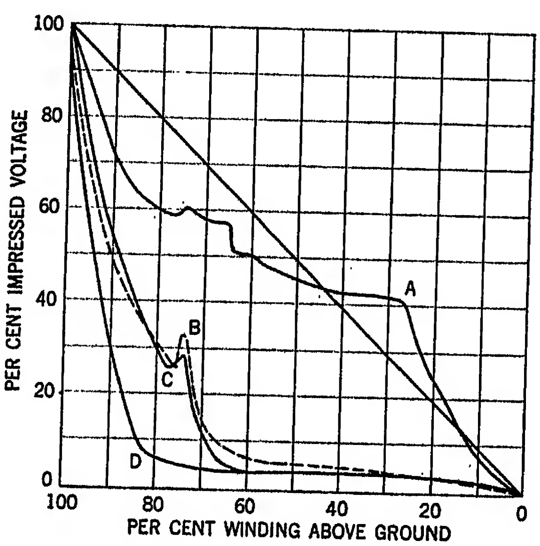

FIG. 11—MAXIMUM VOLTAGES TO GROUND FOR DIFFERENT TYPES OF SURGES

A. Voltage distribution in 3000-kv-a. transformer with 60-microsecond surge
B. Same with chopped surge
C. Same with five-microsecond surge
D. Voltage distribution in 667-kv-a. transformer with five-microsecond surge

the agreement between the curves (Fig. 11), and the oscillograms.

The internal oscillations in general are composed of a fundamental corresponding to the natural period of the transformer with many superimposed harmonic frequencies. It should be noted that the length of the wave affects the composition of the resulting oscillation to the extent of determining the proportions of fundamental and harmonic. For the long wave the fundamental is very large, comparatively, except for the parts of the winding near the line. With the five-microsecond wave the fundamental is reduced and the proportions of the harmonics increased, and, in the case of the chopped waves, the fundamental is entirely absent and only the harmonics exist.

The natural frequency of the shell type transformer investigated was approximately 5000 cycles and that of the core 6700 cycles. It is believed that the order of these fundamental frequencies is representative of that of power transformers in general.

Referring again to Fig. 11, a very close agreement

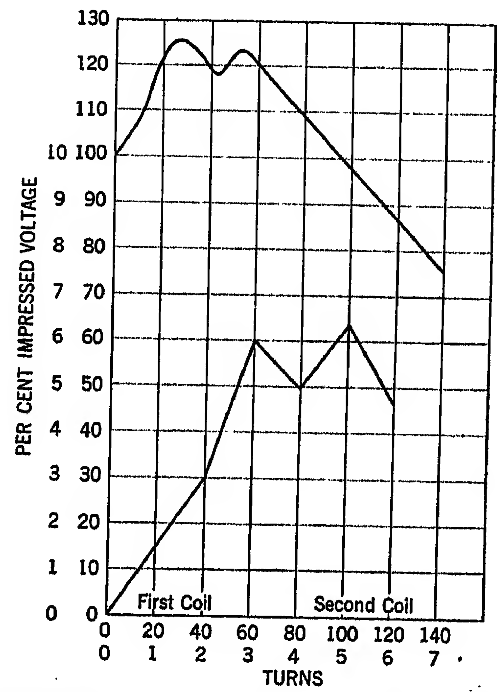

FIG. 12—VOLTAGE DISTRIBUTION IN LINE COILS (FIVE-MICROSECOND SURGE)

A. Voltage across first six turns
B. Voltage to ground in line coils

between the voltage to ground for the five-microsecond and chopped waves is observed. This follows the explanation just given that the initial distribution and not the oscillatory portion of the transient was the factor determining the voltage to ground. This is further substantiated by the agreement between these curves and the curve (Fig. 6) for the initial distribution of a ¼-microsecond front surge.

The breaks or departures from continuous smooth curves were caused by taps in the winding.

The voltage to ground for the 667-kv-a. transformer subjected to a five-microsecond surge is also given. A basis for comparing the two transformers is not simple. However, the curves show for the same surges that 86 per cent of the voltage drop occurs across 15 per cent of

the winding of the 667-kv-a. transformer as against 57 per cent of the voltage for the same percentage of the 3000-kv-a. winding.

Distribution of Voltage in the Line Coils. The division of voltage across the first few turns of the line end of the shell type transformer is given in Fig. 12. This indicates that approximately six per cent of the voltage drop occurs across the first three turns. Data of this nature are very hard to obtain accurately but it is believed that the curve is a fair representation of existing conditions.

When the applied surge is chopped near the transformer, oscillations of a high magnitude exist in the line coils. Such a condition is illustrated in Fig. 13, I and II. The first rise in voltage is due to the initial distribution; following this the terminal voltage is reduced to zero and the oscillations take place about the zero axis. The predominant period is of the order of three microseconds and as the damping factor increases with the frequency, the oscillations are quickly damped out.

The oscillograms III and IV show the oscillations produced in the same coil by the five-microsecond surge

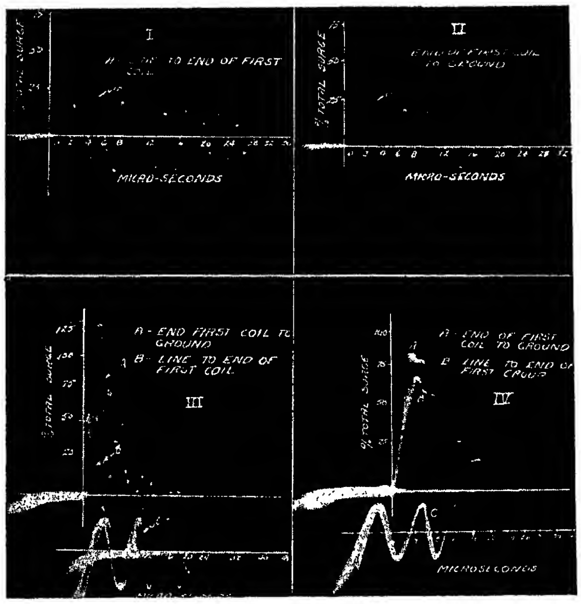

FIG. 13—VOLTAGES IN LINE COIL OF 3000-KV-A. TRANSFORMER

1. and 2. Voltage resulting from surge chopped near transformer
3. Voltage resulting from 5-microsecond surge
4. Voltage resulting from surge rising to maximum and decaying to half value each in 5 microseconds

and a surge with both a five-microsecond front and tail. In the case of the former they are greatly reduced in magnitude and in the latter almost absent. Thus, both the rate of rise and the rate of decay affect the magnitude of these oscillations.

The voltage to ground at the end of the first coil rises to a value in excess of the impressed voltage. This is the result of an oscillation, the energy for which is supplied through both the first and second coils due to the initial distortion of gradient through the first two coils, since the outer layers of these coils are more closely coupled electrostatically than the inner and outer layers of the first coil. Spark-gap data indicate higher than applied voltages to ground throughout the first coil (see Fig. 12B). As points in the second coil were inaccessible only the end points were measured and the curve extended through them.

IV. MAGNITUDE OF STRESSES IN TRANSFORMERS AS DETERMINED BY THE LINE CONDITIONS

Stresses within the Windings. Referring to Figs. 6 and 11 from which the stress along the length of the winding can be estimated and to the probable maximum

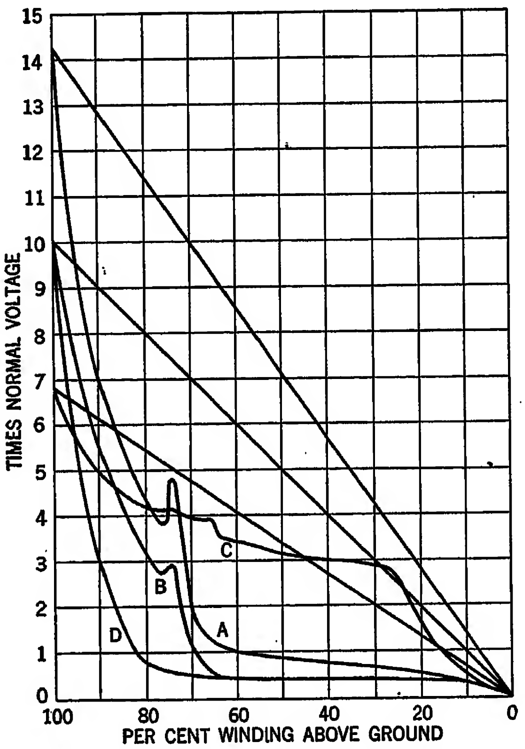

FIG. 14—PROBABLE MAGNITUDE OF INTERNAL VOLTAGES ABOVE GROUND

A. Chopped surge, 3000-kv-a. transformer
B. Five-microsecond surge, 3000-kv-a. transformer
C. 60-microsecond surge, 3000-kv-a. transformer
D. Five-microsecond surge, 667-kv-a. transformer

potentials on transmission line as given in Fig. 1, the following may be deduced.

The highest stresses are evidently those caused by surges with very steep fronts as these give the worst initial distribution of voltage and attain the highest values which, in the case of surges limited by flashover of the line insulation, may be of the order of 14 to 15 times normal. Surges of this character cause no fundamental oscillations on transformers having periods of the order of those investigated herein; therefore, the initial distribution is the only factor necessary to consider. This distribution is largely a function of the physical properties of the winding. It may be seen by reference to the above curves that the greatest stresses occur near the line end where the winding is

made of the simplest possible form of construction, free from taps, which lends itself for providing adequate insulation.

Stresses to Ground. The voltages to ground as expressed in the curves of Fig. 11 have been multiplied by the ratios of the probable maximum surge voltages of Fig. 1 and are plotted with respect to their relative values in Fig. 14. On this basis, the latter curves represent the maximum voltage stresses to ground obtained in the various parts of the transformer winding, either through internal oscillation or by the initial electrostatic induction. In recording these values, measurements by oscillograph and sphere-gap are in agreement within experimental accuracy. Obviously these stresses are placed upon the major insulation of transformers and for uninterrupted service must be withstood. Since in this case, as in the previous case, the highest stresses are produced by the very short surges, the transformer major insulation may be subjected to 14 to 15 times normal voltage in the vicinity of the line end. In the mid-section of the transformer the highest voltages are produced by the long surges and are 3 to 5 times normal. Their value is fixed by the amplitude of oscillation. The amplitude of oscillation is a function of the initial distribution which in turn is a function of the physical proportions of the winding. Transformers insulated sufficiently to withstand the maximum stresses at the line end should without difficulty withstand the stresses imposed at any internal portion, even though the insulation there is reduced.

The above conditions refer to the maximum surges expected in service. For longer surges such as represented by curves E and F, Fig. 1, or for surges removed a considerable distance from the transformer, the stresses would be diminished.

ACKNOWLEDGMENTS

The author is pleased to acknowledge the valuable assistance rendered by Messrs. F. J. Vogel, J. F. Peters, J. M. Blackhall, and others of his associates in the Engineering Department of the Westinghouse Electric and Manufacturing Company in obtaining the experimental data and preparing this paper.

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Discussion

K. K. Palueff: (communicated after adjournment) Mr. Hodnette's contribution consists of an effort in five directions:

First, he gives us a new impulse ratio for transmission-line insulation.

Second, he attempts to show that the initial voltage distribution produced by a traveling wave of steep front can be made more uniform by increasing the width of the coil and shortening the length of the winding stack.

Third, he shows by test (Fig. 6) that in shell-type transformers the initial voltage concentration on the line end is as high as in the core-type transformer tested by him.

Fourth, he expresses his conviction that the natural period of oscillation of all shell-type power transformers is of the order of 5000 cycles.

Fifth, he tells of his belief, that in practise the relation between the length of the traveling wave and the natural period of internal oscillation, of all shell-type transformers, is such that no dangerous oscillation can be created inside of the transformer winding designed for solidly grounded neutral, and having insulation between high-voltage winding and ground and between high-voltage winding and low-voltage winding, graded in the order of operating-frequency voltage stress between the respective parts.

All of the above points were brought up by Mr. Peters, one of the associates of Mr. Hodnette, in his discussions of a paper by F. F. Brand and myself presented at Dallas last May, and have been briefly answered by me in the closing discussion.[1]

Impulse Ratio. The only numerical data so far published on the impulse ratio of line insulators, have been obtained by F. W. Peek. Mr. Hodnette's values of arc-over of line insulators

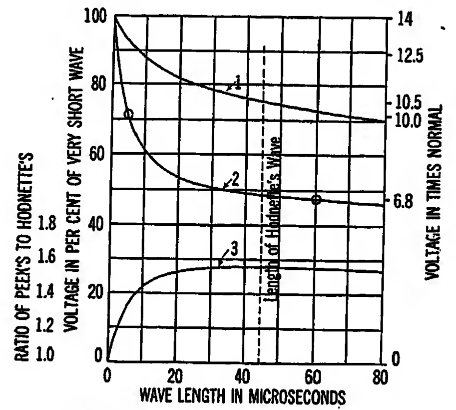


FIG. 1—MAXIMUM LIGHTNING VOLTAGE POSSIBLE

No. 1—Peek's test
No. 2—Hodnette's hypothesis
No. 3—Ratio of Peek's to Hodnette's

by traveling waves of different shapes differ radically from Mr. Peek's. Refer to Fig. 1 of Mr. Hodnette's paper and to Fig. 1 of this discussion. For example, line E of Fig. 1 shows that the amplitude of a wave 60 microseconds long cannot be more than 6.4 times normal, as the normal line insulation would arc-over at that value, provided it would take 14 times normal voltage to arc-over the same insulator string with a wave of a few microseconds. Mr. Peek's data (see Fig. 1 herewith) show that in such a case a wave 60 microseconds long must reach a value 10.3

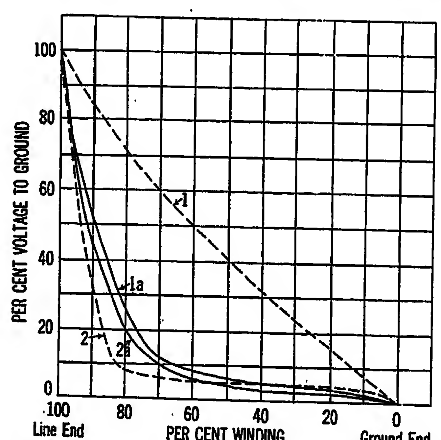


FIG. 2—INITIAL OR ELECTROSTATIC VOLTAGE DISTRIBUTION IN TRANSFORMER WINDINGS

No. 1 —Hodnette's hypothesis, shell type
No. 1A—Hodnette's test, shell type
No. 2 —Hodnette's hypothesis, core type
No. 2A—Palueff's test, core type (without static plate)

times normal before it arcs over the insulators. This fact alone makes all values of internal voltages of shell-type transformers 55 per cent higher than they are shown in the paper (Curve C of Fig. 14).

I should like to know what experimental data were used as a base for Fig. 1.

Initial or Electrostatic Voltage Distribution. Mr. Hodnette found it helpful to employ methods used in my paper of last January,[2] and confirmed by his test, that initial voltage concentrates at the line end of the winding of a complete shell-type transformer to the same degree as in the core type. (See Fig. 6 of Mr. Hodnette's paper and Fig. 2 of this discussion.) It is therefore rather a surprise to me that the author overlooked an

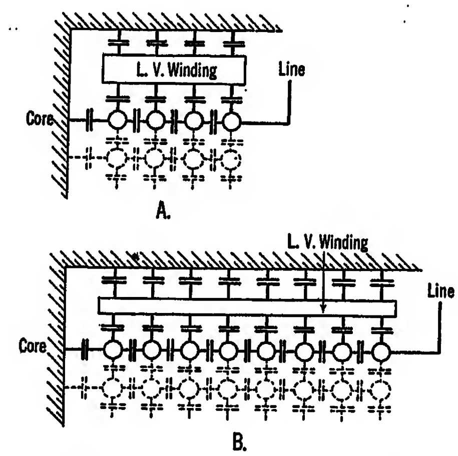


FIG. 3—COMPARISON OF DISTRIBUTED CAPACITANCE IN NARROW AND WIDE COILS

A. Narrow coils
B. Wide coils

exceedingly important fact in his theoretical discussion of the phenomena. Fig. 2 of his paper corresponds to Fig. 19 of my January paper, except that it does not give numerical values of the equi-potential surfaces. Among other things, it shows that considerable voltage drop takes place across the first coil from outside turn toward the inside. This happens because the first coil (as well as all others) at the instant of impact of the traveling wave acts as a chain of condensers composed of the capacitance

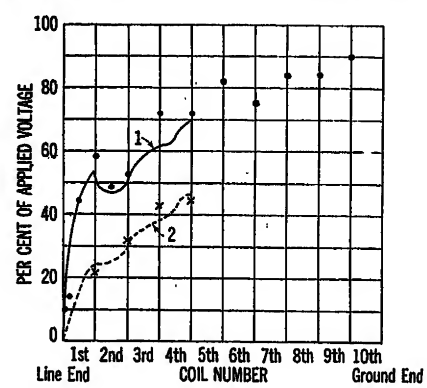


FIG. 4—EFFECT OF COIL WIDTH ON VOLTAGE CONCENTRATION NEAR LINE END

No. 1—Coils 10 in. wide. No. 2—Coils 2 in. wide. The curves are calculated, and the points tested values

between turns as shown in Fig. 3. Mr. Hodnette seems to appreciate this fact, judging by the middle paragraph of p. 70, but in spite of it he tells us that the initial voltage distribution throughout the winding can be determined by the equation given at the bottom of p. 69. This equation would be applicable were individual coils acting as solid metal plates (of width and thickness corresponding to the coil build). Since each coil does not act as a plate, but as a chain of series condensers, the equation is inapplicable. This may be illustrated by the fact that the equation

1. A. I. E. E. Quarterly TRANS., July 1929, p. 989.

2. A. I. E. E. Quarterly TRANS., July 1929, p. 681.

shows that the wider the plates the more uniform the initial distribution. This of course is incorrect, as it is obvious that the wider the coils the longer the chains of condensers to which the coils are equivalent, and the greater the drop in voltage across them.

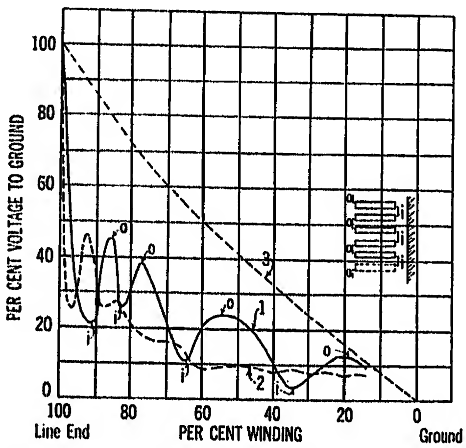


FIG. 5—INITIAL VOLTAGE DISTRIBUTION IN SHELL TYPE TRANSFORMERS

No. 1—Palueff's test, one group
No. 2—Palueff's test, three groups
No. 3—Hodnette's hypothesis

To confirm this theoretically, a detailed equivalent circuit, including capacitance between turns, and from turns of one coil to turns of next coil, as shown on Fig. 3 herewith, was computed for coils of different widths, and calculations made which show very close agreement with results of test (see Fig. 4 herewith).

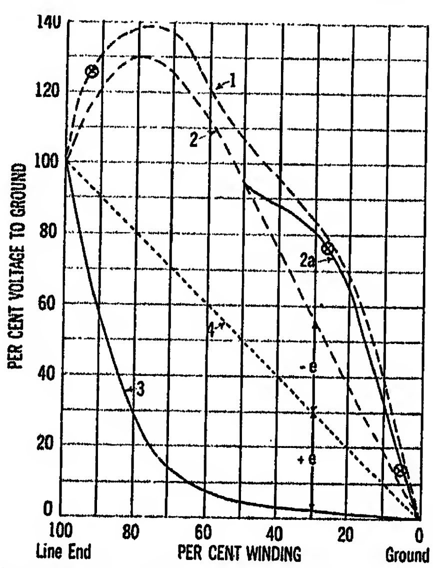


FIG. 6—VOLTAGE PRODUCED BY A SINGLE TRAVELING WAVE

No. 1 —Maximum voltage to ground, Palueff's calculation
No. 2 —Maximum voltage to ground, Hodnette's calculation
No. 2A—Curve 2 corrected according to results of Hodnette's test
No. 3 —Initial or electrostatic distribution
No. 4 —Final distribution, or line of equilibrium. Points shown are from Hodnette's tests

Fig. 5 shows an initial voltage distribution in a 5000-kv-a. shell-type transformer. The saw-tooth shape of the curve for one and three groups must be noted, as this is characteristic of initial distribution of short windings of wide coils. The lowest points of the curve were obtained by measuring voltage of the inside turns (next to the core leg). The peaks of the curve were obtained by measuring the voltage on the outside of the winding. If a curve is drawn through the outside points only, it obviously gives an impression of more uniform distribution than is actually the case. Mr. Hodnette states that the inside points next to the core leg were not accessible in his test. This probably accounts for the smoothness of the initial voltage distribution in shell-type transformers, as shown in his Fig. 6.

The title of Fig. 7 of his paper misled me for the moment, as I took curve *A* for the result of Mr. Hodnette's test of initial voltage distribution in one group of his three-group shell-type transformer, and curve *B* for the same of his core-type transformer. In the body of the paper, however, it is stated that it is a curve of the voltage to ground produced by a 5-microsecond wave. In other words, it is the maximum voltage to ground that occurs in the transformer from the time it is struck with the 5-microsecond wave up to the time when the oscillation completely dies out, and as the initial voltage distribution precedes the oscillation and gives the minimum voltage to ground, the only conclusion that can be derived from his Fig. 7 is that in the particular core-type transformer, which Mr. Hodnette tested, much

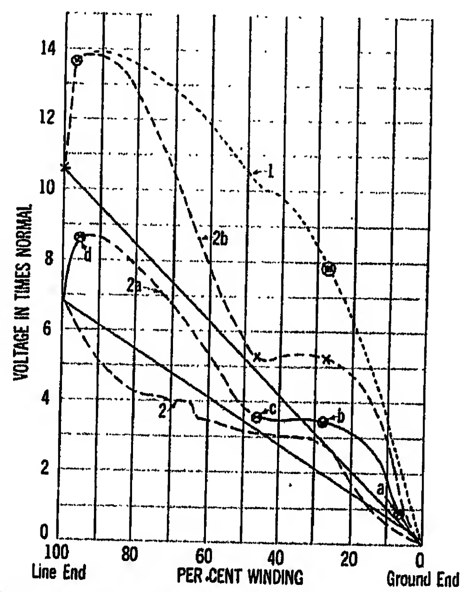


FIG. 7—MAXIMUM VOLTAGE TO GROUND DUE TO A WAVE OF MODERATE LENGTH (SHELL TYPE TRANSFORMERS)

No. 1 —Maximum voltage possible, Palueff's calculation
No. 2 —Hodnette's hypothesis
No. 2A—Hodnette's test
No. 2B—Hodnette's test corrected for applied wave of voltage 10.5 times normal

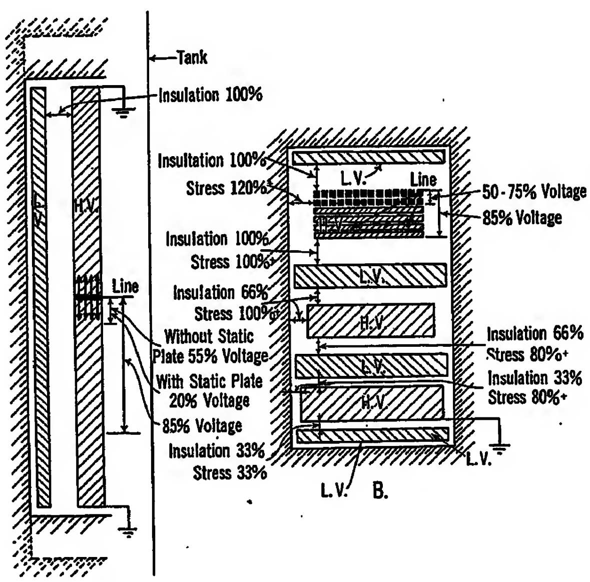
lower voltages to ground were produced by the 5-microsecond wave than in the shell-type transformer used by him, which means that the natural frequency of the shell-type transformer was many times that of the core-type transformer.

I would suggest that Mr. Hodnette check our test and calculations, as shown on Figs. 4 and 5 herewith, by using the winding of a transformer that he considers to be "well proportioned." However, it would be quite necessary to measure voltage between line end and all inside and outside turns of the coils.

The calculation and the test will show immediately that the initial distribution grows worse as the width of the coils increases and on account of the fact that the stack becomes shorter as coils increase in width, the voltage per unit length of the stack increases. The comparison of these stresses in the short and long stack is shown in Fig. 8 herewith, where a cross section of core and shell-type transformers, having approximately the same bulk of winding, is drawn to the same scale, and the insulation distribution and voltage stresses, due to initial distribution and subsequent oscillation, are given.

Fig. 6 of the paper shows that at the initial moment 46 per cent of the applied voltage of a steep wave appears across 6.7 per cent of the winding in the so-called "well proportioned" shell-type transformers. Curve B of his Fig. 7, which Mr. Hodnette considers to give very nearly the initial distribution in the core-type transformer, gives 50 per cent of applied voltage across the same percentage of the winding. Does not the author think that this is good evidence, since the initial voltage distribution is so nearly alike, in two windings so radically different that our opinion is correct, that in practical transformers it is quite impossible to appreciably modify the initial voltage distribution by a mere change in the width and the length of the stack?

In the light of the above, I should very much appreciate it if the author would explain to us the reason for classifying as well proportioned the shell-type transformer that he tested? The reason becomes particularly obscure, since the author himself emphasizes that in shell-type transformers about 85 per cent of the applied voltage appears across the line group, that is, across $\frac{1}{8}$ or $\frac{1}{4}$ of the entire winding, depending on the number of



A.

FIG. 8—COMPARISON OF VOLTAGE STRESSES AND INSULATION IN GROUNDED NEUTRAL TRANSFORMERS

A. Concentric type, not graded
B. Shell type, graded insulation

groups. In my opinion the goal of a designer should be to get a uniform initial distribution, and not that of his Fig. 6.

Internal Oscillation and Voltage to Ground. In my paper presented last January, I stated that both core and shell-type transformers undergo a violent internal oscillation when struck by a single traveling wave.

It appears from the discussion that the tests of some of Mr. Hodnette's associates showed such oscillations in shell-type transformers. I am, therefore, particularly glad to see that further study, as revealed by his oscillograms Figs. 9 and 13, confirm in all respects our conviction that the oscillation of shell-type transformers is of the same magnitude as that of the core-type. The shell-type transformer, as theory shows, has also certain additional oscillations peculiar to that type, but lack of space here does not allow going into the phenomena at length.

On Fig. 6 herewith, Curve 1 is an envelope of maximum voltage to ground possible in a long stack of narrow coils. This curve is copied from Fig. 4 of *Lightning Study of Transformers by Cathode Ray Oscillograph.*[1] Encircled crosses correspond to the values obtained from Mr. Hodnette's oscillogram No. 1 of Fig. 9 and Curve A of Fig. 12. Incidentally, these points of Mr. Hodnette's test exceed materially his theoretical curve of maximum voltage to ground (Curve C of Fig. 4), as should be expected since the method employed by him for constructing Curve C is in radical conflict with requirements of the theory, described in detail in both of our above mentioned papers.

Further similarity of oscillations in the two types of transformers is shown by comparison of amplitudes of the oscillations produced by a 60-microsecond wave at the 47 per cent point of the winding of the shell-type transformer (see Plate II of Fig. 9) and at the 50 per cent point of the winding of the core type transformer (see Fig. 10).

As shown in my January paper, there is a very simple relation between the length of a traveling wave and the amplitude of maximum voltage to ground created by it in a transformer winding. This relation is a function of the ratio of duration of half of a period of the first few natural frequencies of a transformer and the duration of the applied wave. Mr. Hodnette's test shows that in his shell-type transformer the natural frequency happened to be 5000 cycles, and that of the core-type transformer to be 6700, and by assuming that the longest dangerous lightning wave is not more than 60 microseconds, he arrives at Curve A of Fig. 11 (by scaling oscillograms of Plate II, Fig. 9) as an envelope of maximum possible voltage to be expected in service in any power transformer of shell type. There are several objections to this conclusion.

1. Referring to Fig. 7 of this discussion, encircled crosses a, b, and c were obtained by measuring more accurately oscillograms of Plate II, Fig. 9. Point d is taken from Curve B, Fig. 12. Comparison of these points with the Curve C of Fig. 14 shows that the curve is from 10 to 50 per cent below the true values, as shown by the oscillograms.

2. Since the voltage to ground increases with an increase in the length of the applied wave, it is very essential to know accurately the length of the wave that produced the voltage indicated by points a, b, and c. Mr. Hodnette considers this wave 60 microseconds long, but observing the fact that neither time nor voltage scale of Plate II, Fig. 9 is uniform, and exercising all necessary care in scaling the oscillograms, it appears that the wave is not 60 but 47 microseconds long. The theory shows that were the wave really 60 microseconds long, it would produce voltages in excess of even those shown by a, b, and c.

3. If the natural frequency of the transformer were not 5000 cycles but, say, 10,000 cycles, then as theory shows, half of the winding next to the neutral end will practically reach Curve 1 of Fig. 7 of this discussion when the transformer is struck by a 60-microsecond wave. The same would happen if the natural period of the transformer were 5000 cycles, but the length of the applied wave were 120 microseconds. Mr. Hodnette's opinion that all shell-type transformers have a natural frequency not materially higher than 5000 cycles rests on the supposition that the presence of an interleaved low-voltage winding increases the effective capacitance of the high-voltage winding to ground and prevents the natural frequency rising substantially above 5000 cycles. On Table I of this discussion, results of cathode ray oscillograph tests of natural periods of various transformers are given, which show very wide variation in the natural period in accordance with theoretical conclusions published in my January paper. They also show that the minimum and maximum natural frequencies of shell-type and core-type transformers tested covered about the same range.

The fact that the 5-microsecond wave produced voltage to ground in the short stack of wide coils as shown by Curve A of Fig. 7, indicates that the natural frequency of that particular stack was very much higher than 5000 cycles, and substantially higher than that of the core-type transformer that gave the voltage distribution shown by Curve B of the same figure.

On the strength of all of the above, we can revise Mr. Hodnette's Curve C of Fig. 14. The results are shown on Fig. 7 of this discussion. Curve 2 is a copy of Mr. Hodnette's curve C of

Fig. 14, which is supposed to be an envelope of maximum voltage to ground produced by a 60-microsecond wave of the maximum amplitude possible in service.

Curve 2a is the revision of this curve in accordance with Mr. Hodnette's own oscillograms, as mentioned before. Curve 2b is the revision of curve 2a, with the amplitude of the applied wave increased from 6.8 times normal to 10½ times normal on account of the difference in impulse ratio given by Mr. Peek and Mr. Hodnette for the 47-microsecond wave. (See Fig. 1 of this discussion).

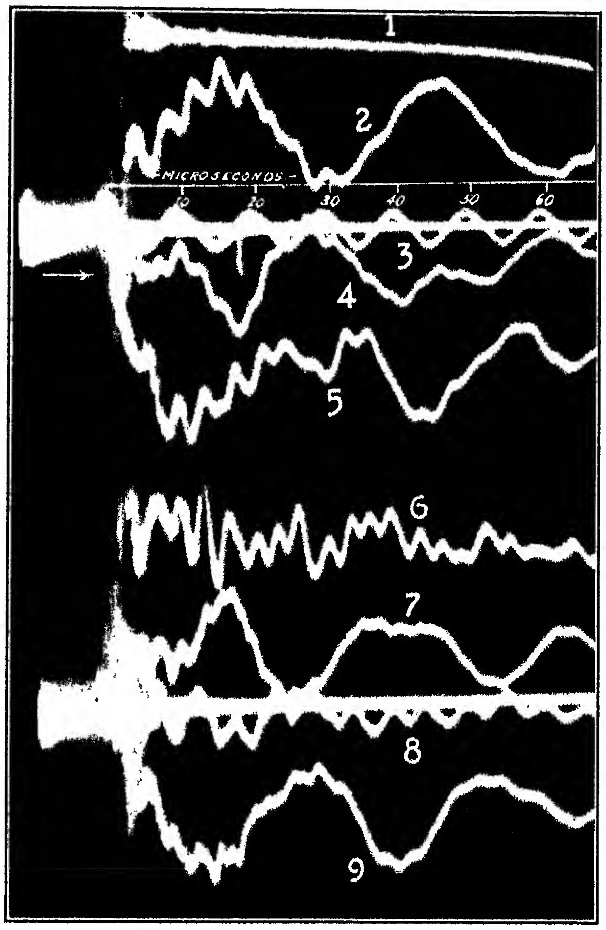


FIG. 9—INTERNAL VOLTAGES IN ONE-GROUP SHELL TYPE TRANSFORMER

No. 1—Applied wave. No. 2—Voltage 50 per cent from ground end. No. 3—Timing wave. No. 4—26 per cent from ground. No. 5—78 per cent from ground end. No. 6—91 per cent from ground end. No. 7—32 per cent from ground end. No. 8—6 per cent from ground end. No. 9—59 per cent from ground end. Nos. 4, 5, 8, and 9 were obtained with reversed polarity

Dotted Curve 1 represents the maximum possible voltage to ground calculated for a long stack of narrow coils. The encircled point on it was taken from Plate 1 of Fig. 9 of Mr. Hodnette's paper. This proves that the voltage that would appear in shell-type transformers, at least at that particular point of the winding, rises far in excess of the strength of graded insulation at that point, and reaches the same value as in a long stack of narrow coils. That the necessary relation of the natural period of shell-type transformers and the length of the applied wave is possible, is substantiated by Table I of this discussion, and Curve *A* of Fig. 7, as well as by theoretical considerations.

I did not find in the paper either test data or theoretical estimates of voltage stresses that may be produced in a shell-type transformer by a damped switching transient. Since the shell-type transformer has a number of natural frequencies, it may get in resonance with the transmission line. This will produce very high internal voltages. I should like to know just what are the author's findings in this branch of the phenomena.

On account of all of the above, I feel that we must remain of the opinion that grading of major insulation in the order of low-frequency stresses is not a safe practise. This is substantiated by service experienced with some modern transformers built with graded insulation, which have failed during a lightning storm at a point on the winding far removed from the line end.

TABLE I
NATURAL FREQUENCY OF POWER TRANSFORMERS

Type	Capacitance kv-a.	Fundamental natural frequency in kilocycles	Duration of natural period in micro-seconds	Second natural frequency in kilocycles	Duration of second natural period in micro-seconds
Shell	2,000	40.	25.		
Shell	2,500	33.4	30.		
Core	3,300	33.2	30.	100.	10.
Shell	1,000	11.0	90.	40.	25.
Core	22,000	10.5	95.	37.0	27.
Core	23,300	16.7	60.	80.0	12.5
Core	12,000	12.9	77.4	65.0	15.0
Core	6,670	9.0	111.	31.0	32.
Shell	5,000	6.25	160.	25.	40.
Core	8,000	6.40	157.	28.8	35.

	Shell type	Core type
Lowest fundamental frequency (kilocycles)........	6.25	6.40
Highest fundamental frequency (kilocycles)........	40.0	33.0

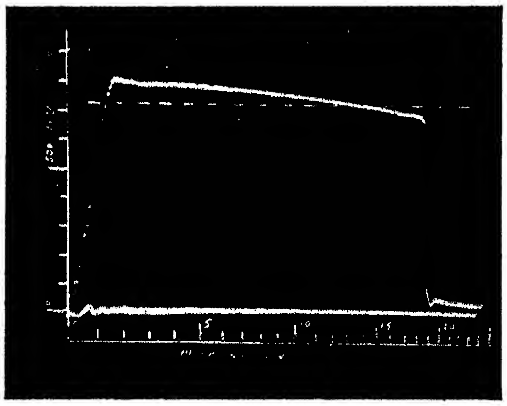


FIG. 10—CATHODE RAY OSCILLOGRAM OF THE SURGE FLASHOVER OF A LINE INSULATOR

F. W. Peek, Jr.: I find Mr. Hodnette's paper of great interest because the subject has been a hobby of mine for a long time.

The first test of this nature was made about 1913. There were some very peculiar failures far in the interior of a transformer winding and the only apparent cause was some high-voltage phenomenon due to arcing grounds or lightning. However, it did not, at that time, seem possible that very high frequency or lightning voltages could penetrate the very high inductance of a transformer. An investigation was started by applying high-frequency currents to transformer terminals. High voltages were built up even at the ground end. This was surprising. However, the mystery was soon solved when it was realized that, while a transformer was an inductance at operating frequencies, it was largely a capacitance at high frequencies.

At 60 cycles or for direct current or any low frequency, the applied voltage divides along a transformer stack in proportion to the inductance or the resistance. The voltage distribution is caused by these factors and is thus very good. When a high-frequency or steepfront voltage is applied to a transformer the voltage distribution at the first instant is controlled entirely by the capacitance. This capacitance distribution is always such that the voltage becomes practically all concentrated on a few turns of the winding near the line end. After a short interval of time has elapsed, the inductance must become the controlling factor. In passing from the transient distribution stage to the final or inductance distribution stage, the voltage over-shoots and oscillations occur. In this manner extremely high local voltages may be caused in any part of the winding.

The above characteristics apply to either a shell-type or to a core-type transformer. In fact the original failure and the original investigations were on shell-type transformers. The first step in improving this transient condition was a change from the shell-type to the core-type transformer. While this was an improvement it was the ambition of the engineers interested in this investigation to produce a transformer that would not resonate, or, in fact, that would have the same voltage distribution under all conditions of frequency or impulse. This has been accomplished in the shielded winding, or non-resonating transformer recently discussed before the Institute.[1,2] The means employed are quite simple. A shield is added to the transformer in such a way that the capacitance distribution corresponds to the inductance distribution. In other words, in the shielded winding, whether the distribution is caused by the capacitance at high frequency or by inductance at low frequency, the voltage gradient is uniform throughout the winding. Since the initial and steady-state distribution are thus the same, there can be no oscillation. By this arrangement local stresses are reduced as much as 80 to 1. Besides the enormous strength of such a transformer under the voltage transients incidental to operation, it has an additional advantage in that the 60-cycle acceptance test is the equivalent of a lightning test. This follows because of the uniform voltage distribution at any frequency.

There may be some question as to whether or not a transformer is subjected to the same frequencies or impulses in practise as were used in making tests in the laboratory. The original test covered a very wide range of transients and impulses. Cathode ray oscillograms of lightning which have been obtained this year and last show quite conclusively that the worst laboratory effects would occur on practical lines. The highest voltages to which transmission lines are subjected are caused by lightning. As a general rule, the maximum voltages caused by switching or arcing grounds are approximately half the lightning voltages. Accordingly, switching surges have practically no influence on line insulation. It so happens, however, that surges of the type caused by switching, because they are oscillatory, build up about twice the voltages that are built up by single impulses for the same applied voltage. The effects are thus, on many lines, equal.

It is my opinion that the non-resonating transformer is one of the greatest advances made in the art in the last 20 years.

F. E. Terman: After we have been working with transformers for a while we get accustomed to think that the voltage between two points of a coil will be proportionate to the number of turns within those two points. I want to point out that there are some types of coils in which that is not the case.

In an air-core coil the linkages per turn are less at the ends of the coil than at the center. As a consequence, with air-core coils such as used for radio we get a coil with a higher voltage rating by spreading out the center turns and bunching them together at the end.

Mabel Macferran: I should like to inquire what effect a reactor in the neutral of a Y-connected bank would have on the resonance phenomena under discussion.

Alexander Nyman: The subject of Mr. Hodnette's paper has long ago been recognized by designers of transformers. It has been usual to take account of these phenomena by proper insulation of the end turns of transformers, but in spite of that, occasional disturbances of great magnitude have caused breakdowns.

The value of this paper lies therefore in summarizing the results of the recent studies on lightning disturbances and other surges and applying these results to the study of transformer operation so as to give a clear picture of the phenomena that take place.

It appears that the main reason for the unequal distribution of voltage through the windings of the transformer, when subjected to a surge, is the fact that the distribution of capacity between the coils and from coils to ground throws an excessive burden of initial surge voltage on the turns closest to the line. It is evident, of course, that if the capacity to ground of these coils is reduced relatively to the capacity between coils, the distribution of surge voltage would be more even. In a limiting case, if all of the distributed capacity to ground were eliminated and the capacity between the individual coils were the same throughout, the distribution of surge voltage would be exactly the same as the distribution of 60-cycle voltage. Of course, such a condition is impossible to reach in practise, but it is possible, and entirely feasible, to work in the opposite direction and to increase the capacity between the coils, as compared to the capacity to ground. The easiest way to achieve this is to introduce static condensers external to the transformer coils but connected to them at intermediate points.

Condensers to withstand high voltages and to pass surge currents of considerable magnitude have been developed and can be built in such small physical dimensions for the required capacity that they can be easily installed within the transformer tank and constitute a part of the final assembly of the transformer structure before immersion into a tank. For example, a condenser to withstand a 60-cycle voltage of 10,000 would occupy a physical dimension of 4 by 6 by 10 inches for a capacity of about 0.01 microfarads. Thus, if a number of units of this size be built up into a structure, with taps brought out corresponding to the voltages on the individual coils, it is quite evident that the resulting capacity will be far in excess of any capacity to ground that may exist from the corresponding coils, and therefore voltage distribution due to surges will be practically equalized. The condensers of this nature have been subjected experimentally to surge tests and are known to withstand a surge voltage of at least ten times the operating 60-cycle voltage. Since the author states, as a result of his investigation, that the voltage seldom exceeds double the line voltage and never exceeds five times the line voltage, it is evident that such a condenser would be quite safe, and moreover, on account of its large capacity, it will have a tendency to take over the peak of the surge, due to its steep wave front.

J. K. Hodnette: Apparently Mr. Palueff has incorrectly interpreted the object of my paper. The intention was not to prove that Mr. Palueff was wrong in any respect or to present the real merits and demerits of shell- and core-type transformers, but the object was to present additional data on the general subject and coordinate previous data.

In Mr. Palueff's discussion he stressed the idea that the voltage distribution was substantially the same in all non-shielded transformers. I strongly disagree with this. In the paper of Blume and Boyajian published in February 1919, which Mr. Palueff correctly refers to as a classic, you will find that the value α which corresponds to the term $\sqrt{\dfrac{C g}{C c}}$ in my paper, $C g$ being the capacitance to ground and $C c$ the capacitance between coils. They further state that α is found to vary between 5 and 30 for disk-type windings. It was not my intention to point out the relative values of the constants of shell- and core-type

transformers. But it is easily seen that this ratio is much smaller for the usual proportions of shell-type transformers than for the usual proportions of core-type transformers. Therefore, generally, the initial voltage distribution would be better for wide-coil transformers than for narrow-coil transformers.

With reference to the discussion on the initial or electrostatic voltage distribution, it is conceded that the problem becomes very complicated to predetermine the voltage at some particular point in a winding unless the elements of the winding are considered as being solid plates. This is the very assumption made in both Mr. Palueff's and Mr. Peek's work in connection with the shielded transformer. Otherwise they could not apply shields, effective on the edges of the coils only, and obtain a uniform distribution of voltage throughout the windings of the transformer.

It is necessary to define a wave with respect to time when determining its effects. This has been carefully done in the body of this paper. The wave shown in Fig. 10 of this discussion was used as a basis for computing Curve E, Fig. 1 of the paper. This wave would have decreased to one-half value in approximately 50 microseconds had the insulators not flashed over and reduced it to zero at 19 microseconds. In this oscillogram the dotted line represents the 60-cycle flashover voltage, and with this wave the impulse is 6.4 times normal instead of 10.3 as stated by Mr. Palueff. Therefore, in comparing the voltage stresses they should not be increased by the ratio of 10.3 to 6.4 but are correctly represented in Fig. 14.

The curves given in the experimental section of my paper were obtained by measurement directly from the original oscillograms and checked by sphere spark gaps, the standard for measuring high voltages. Therefore, I cannot agree with Mr. Palueff that these values are so far in error.

It has not been my intention to give the impression that all transformers have a natural frequency of 5000 cycles. Power transformers of modern design over a wide range in size have been tested and natural frequencies as high as 12,500 cycles recorded, but a frequency of 5000 cycles is considered a representative value in order of magnitude. In this connection, Fig. 9 was given to show the variation in amplitude attained by internal oscillations with the variation in the length of applied wave. The waves used covered sufficient range in length to show the effect of any fundamental frequency expected in modern commercial transformers when subjected to natural lightning surges. As indicated, transformers having a higher fundamental frequency would have internal stresses somewhat increased but not sufficiently to alter any of the conclusions drawn.

Curve A, Fig. 7, is a measure of the maximum voltage to ground produced by a 5-microsecond surge, but at the same time it is a measure of the initial distribution of voltage as the natural frequency is such that the initial voltage is also the maximum voltage to ground. This curve was determined by measuring the voltage at the starts and finishes of every coil.

The company with which I am associated has supplied a large number of graded-insulation shell-type high-voltage transformers which are operated in very severe lightning districts. It is definitely known that lightning has struck the lines close to several banks of these transformers with no disastrous results to the transformers, in spite of the fact that these lines were considerably over-insulated. This does not prove conclusively that these transformers or any transformers are immune from all possible lightning strokes but it does indicate their adequacy for this service. It is only necessary to refer to service records in general to learn that failures to ground through the major insulation of such transformers is practically unheard of.

With reference to Mr. Peek's discussion, it may be of interest to note that the company with which I am associated has been building both shell- and core-type transformers for many years. Contrary to Mr. Peek's conclusions, laboratory tests and service records do not indicate that the core-type transformer is superior to the shell-type. The type of construction best suited for a particular application is generally used.

Analyzing Miss Macferran's question concerning the effect of connecting a reactor between the neutral of a bank of transformers and ground, it is possible for the reactor to enter into oscillation with the transformer and somewhat increase the voltage on the grounded end. The degree to which the reactor effects the oscillations here depends upon the characteristics of the reactor and of the transformers and the shape of the surge striking the transformer terminal. For a short surge, such as the 5-microsecond surge, it has been shown that only a small amount of energy penetrates the winding to the portion near the grounded end, consequently the potential at the reactor will be low. For a long surge more energy passes through the winding and the oscillations at the reactor will be proportionately increased as in the case of the transformer itself.

Mr. Nyman has attacked the problem of improving the voltage distribution in the opposite phase from that described by Mr. Peek. In so doing he has reached a perfectly logical conclusion. I completely agree with him that the distribution can be improved by increasing the relative capacitance between coils, as this in turn decreases the ratio of the capacitance between coils. However, the introduction of condensers in the transformer means the addition of another device or complication in the construction and it is desirable to keep the construction as simple as possible.

Mr. Terman has illustrated an interesting method of effecting a good voltage distribution in air-core coils but I do not believe that it is applicable to power transformers.

An A-C. Low-Voltage Network
Without Network Protectors

BY LESTER R. GAMBLE[1]
Member, A. I. E. E.

and

EARL BAUGHN[1]
Associate, A. I. E. E.

Synopsis.—*The object of this paper is to present a description of the Spokane, Washington, underground network system, and to describe briefly the operating experience and problems which have resulted from the installation of ring primary feeders and a four-wire, 120/208 volt secondary network supplying a universal service.*

Reasons for the choice of the system described are presented with particular reference made to the use of a fuse in the secondary circuits instead of the device commonly known as the "Network Protector."

The general design of the primary feeders, secondary network, pilot wire relays and fuse protection, and transformer vaults is discussed.

Descriptions are given of all apparatus and equipment used.

A report is included covering tests made on the system under fault conditions. The report shows that the tests which simula ed actual operating conditions indicate the system will operate as designed. The voltage regulation of the network having been recently investigated, is covered in detail.

The procedure in the change-over from d-c. to a-c. service is discussed and the problem of customer consideration analyzed.

The paper is concluded with a statement that no difficulties have been encountered on the system and that its operation up to this time has been perfect.

Introduction

In 1923 a general survey was made of the three-wire Edison d-c. system, which served the downtown business district in the city of Spokane, Washington. The survey indicated that the demands for electric service were placing many limitations on the d-c. system. Some of the limitations were: (a) excess transmission loss; (b) poor voltage regulation; (c) limited duct space because of the large number of feeder cables required; (d) limited feeder capacity because of the inability of duct lines properly to dissipate energy losses.

However, the d-c. system had been very satisfactory considering the continuity of service. There had been very few cases of trouble, with a record of only one complete interruption since the mains and feeders were placed underground in 1910. Because of this excellent record there was considerable opposition to any suggestion of substituting an a-c. system in the downtown business area. It was realized that such a substitution positively eliminated the stand-by battery, which gives to the d-c. system its high standard of service.

Nevertheless later investigations showed that the industrial customers, in general, preferred a-c. service, because of the lower first cost and the lesser maintenance required in the operation of the a-c. motor and its control equipment. Also, that numerous requests were being made for a-c. service for neon signs, a-c. radio sets, radio broadcasting stations, telechron clocks, and many other uses where alternating current is necessary or preferred.

Fig. 1A shows the area as originally covered by the Edison d-c. system. Areas Nos. 1, 2, and 3 represent the territory served by underground distribution and area No. 4, that served by overhead distribution. The system was supplied from the substation located as shown on the sketch.

1. Both of the Washington Water Power Company, Spokane, Wash.

Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.

Area No. 1 with a d-c. load of 7000 kw. represents the heart of the downtown district and is the area having the highest load density. Area No. 2, which had a d-c. load of 1000 kw., represents the district changed over to a-c. network operation in the fall of 1928. Area No. 3, with a d-c. load of 2300 kw., represents the section which will be changed over during 1929 and 1930. Area No. 4 represents the overhead d-c. dis-

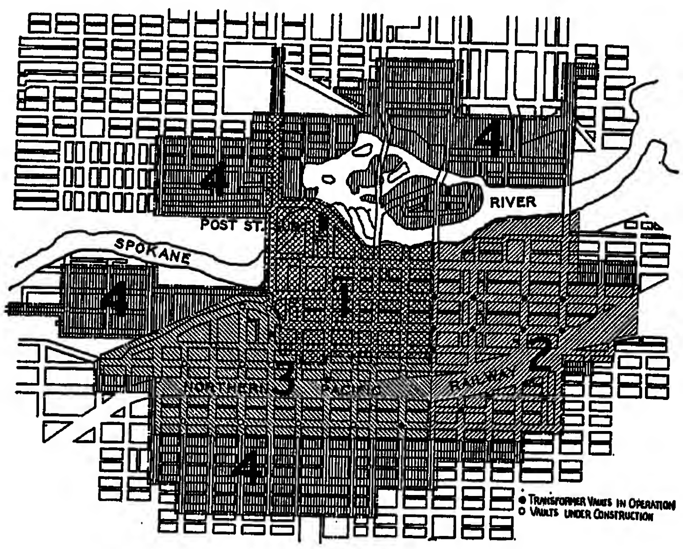


Fig. 1A—Spokane Business District

tribution system which was changed over to a radial a-c. distribution system during 1925, 1926, and 1927. This latter area, with a load of 1000 kw., contained residential, warehouse, and industrial customers whose service requirements did not seem to demand the high quality of service needed in commercial districts represented in areas 1, 2, and 3.

It will be seen, by the above, that the plan was to limit the growth of the d-c. system by surrounding it with an a-c. network system, which would make it unnecessary to expand the d-c. service into new districts.

After changing over the outer districts the d-c. system will be further curtailed by extending the a-c. network into the central area.

Type of A-c. System Selected

In order to overcome the limitations of the downtown d-c. service as cited above, it was apparent that large expenditures were necessary and at the same time it was recognized that the income from the service rendered could not justify the expenditure of any considerable sum of money. Therefore, a number of plans was considered and an attempt was made to provide an economical system without the sacrifice of reliability and quality of service.

After comparing the d-c. system with an a-c. system having equal reliability, it was found that the a-c. network supplying a combined light and power service.

The ring type of feeder seemed preferable to the radial, first, because it made it possible to give a two-way feed to certain isolated loads, which could not be connected to the secondary network and which due to their importance would require a very expensive service from two primary feeders with special throw-over equipment, and second, because an analysis of the annual costs of the two types of feeder systems (ring and radial) gave for the particular shape of area to be supplied, a somewhat lower cost for the ring feeder. Although the costs of the two types were relatively close, it was apparent that the characteristics and shape of the area served made the ring type feeder more desirable. However, in comparing these costs, cognizance was taken of the advantage the radial

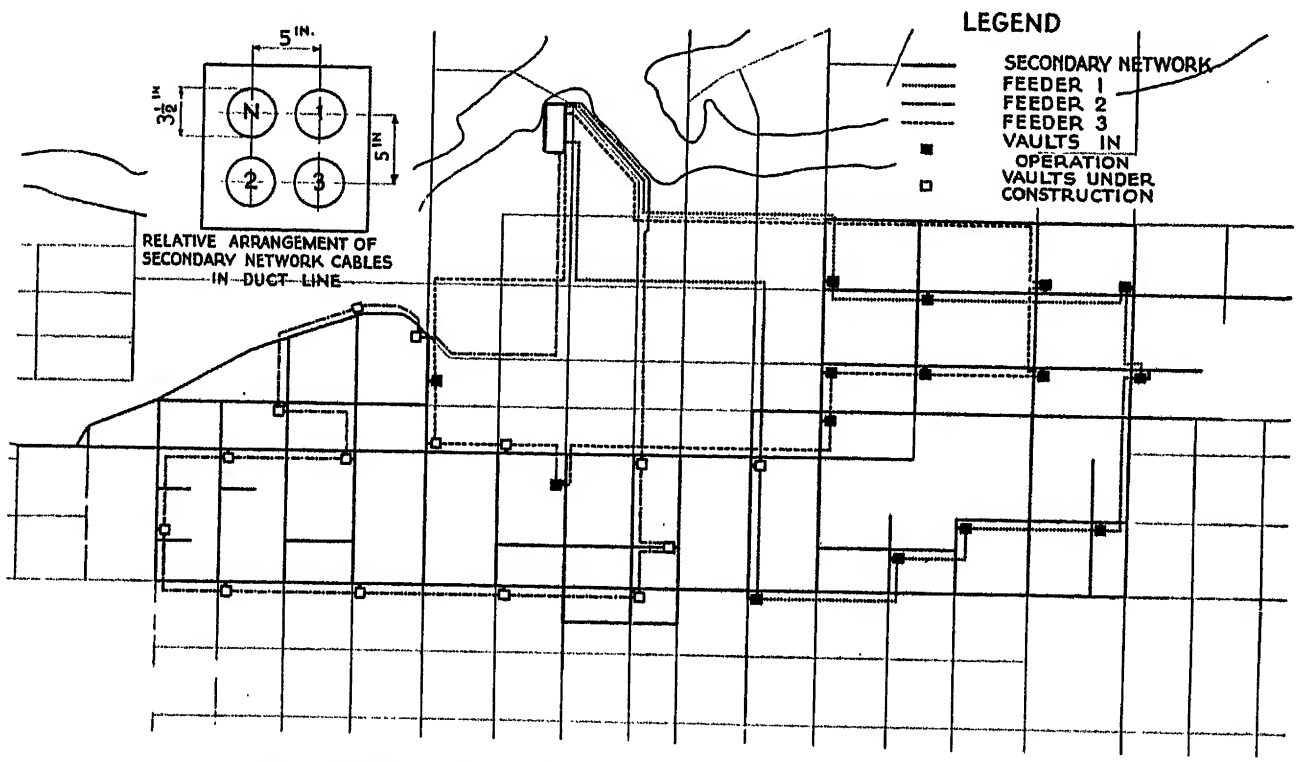


Fig. 1B Secondary Network and Primary Feeder Arrangement

system had certain outstanding advantages, namely, high efficiency and low cost per kilowatt delivered.

The particular type of a-c. system decided upon was determined after making a thorough investigation of all types of a-c. systems then in use in various parts of the country. No one system was taken in its entirety, but parts of several systems were combined into one, which it was felt would give Spokane's commercial area a distribution system of the highest order and one which would have no part or element that had not been tried out in service.

The system adopted consists of three-phase, 4000-volt primary ring feeders, sectionalized by oil circuit breakers operated by means of a pilot wire relay circuit, and a three-phase, four-wire, 120/208-volt secondary feeders offered to the saving of certain amounts of transformer excitation losses during light load periods, by taking one or more feeders out of service.

The primary voltage to be used was given considerable study and after a thorough investigation of the future load requirements it was found that 4000 volts would be the most economical voltage. This was governed particularly by the fact that the substation supplying the load would be within approximately 2000 ft. of the load center, and thereby defeat the necessity of higher voltages to secure better regulation and reduce losses.

The plans for an a-c. secondary network were adopted, at the beginning, because it was felt that the high standards of service which had been provided by the

d-c. network should in no way be lowered through the substitution of a radial type of secondary.

The plan of combined light and power service was selected because of the savings attendant to such a type of system, notwithstanding the fact that such a system had certain inherent disadvantages which must be eradicated by proper design features. These features are discussed at length throughout the paper.

Because of the particular type of primary feeder installed, the protective and sectionalizing devices which have been used are radically different from those used on systems with radial feeders. In general, the device known as the "Network Protector" has been used in other cities for sectionalizing faults on such systems. With the ring feeder, however, the network protector does not become an absolute necessity, especially where fuses can be used effectively to accomplish the same result. Fuses ranging from 800 to 2000 amperes in capacity can be substituted very satisfactorily. The positive action of the fuses used in

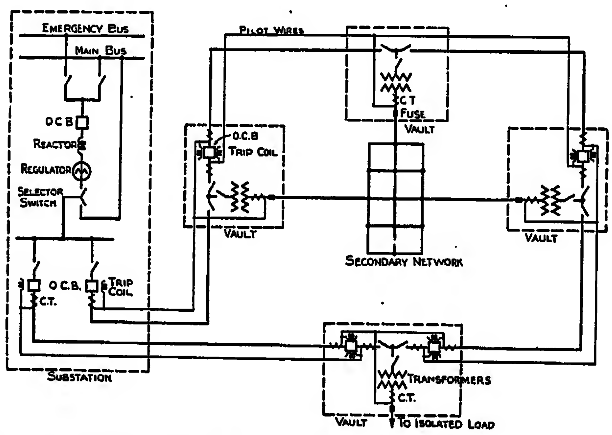


Fig. 2—One-Line Diagram of One Primary Ring Feeder

the Spokane system is apparent from the fact that under no condition of fault in the primary feeder do currents to the fault flow from the low-voltage network, through more than one fuse.

Description of System

Power Supply. The power supply for the Post Street Substation on which the a-c. underground network is entirely dependent is obtained from five independent sources, namely, the Upper Falls, Monroe Street, Nine Mile, Long Lake, and Little Falls hydroelectric plants. Of these, the first two are located in the city of Spokane and generate at 4000 volts and supply power directly to the bus to which the feeders are connected. The power from the other three plants is carried over 60-kv. and 110-kv. lines and brought into the substation over several 13-kv. distribution circuits.

This gives a number of power sources connected to the main substation and provides a very reliable service to the network system, where service continuity is of the utmost importance.

Substation Equipment and Bus Arrangement. The layout of the system from the substation to the secondary network is shown schematically in Fig. 2. The feeders are connected to either one of two buses, thence through reactors and regulators to an auxiliary bus where the feeder divides into two parts, forming the ring feeder.

The arrangement of the main oil circuit breaker, reactors, and regulators is such that in case of trouble in any of this equipment it can be by-passed conveniently without interrupting the feeder.

There is a set of three single-phase regulators on each feeder. No special connections have been used between different sets of regulators to obtain stable operation. It has been found by other users of the a-c. network that stable operation is possible if due care is taken in setting the line drop compensators. On the Spokane system the regulators on each feeder are set to regulate on the low side of the transformer which is situated nearest the load center of the feeder involved. This, it will be seen, approximates very closely the rule for stable operation as laid down by Mr. Blake,[2] where he states that no hunting of regulators will occur if the compensators are set to regulate for something less than one-half of the total impedance of the primary feeder and secondary network.

Primary Feeders. The primary feeders consist of three-conductor, 250,000 cir. mil, 4000-volt, paper-insulated, lead-covered cables. Each feeder is rated at 300 amperes and has a capacity of 2000 kw.

Area No. 2 is at present supplied from two such ring feeders. Although these feeders have a capacity of approximately 4000 kw., the area which is being supplied, at this time, places on them a load of about 1500 kw.

Area No. 3 which will be changed over to a-c. operation during 1929 and 1930 having 2300-kw. load, will be supplied from the present two feeders and also an additional feeder.

With the installation of a total of three feeders, approximately 6000-kw. load can be supplied. The three feeders will cover the area of the underground system sufficiently so that it will be possible at any time to add transformer vaults and change over loads in the more densely loaded district.

The feeders are interlaced and the transformer vaults connected so that by the loss of more than one section of a ring feeder or, by chance, the loss of the entire feeder, the service on the secondary network can be maintained. If such a condition should occur at peak load there would be possibly, in some remote sections, a drop in voltage, usually of a relatively small amount. However, the loss of two sections of the same feeder simultaneously or the loss of one complete feeder is so remote that no apprehension is felt regarding the service.

The area which will be covered by the a-c. low-

2. *General Elec. Rev.*, May 1928, p. 248.

voltage network when the present construction program is finished, is shown in heavy lines on Fig. 1B. The location of the vaults in operation and under construction, together with the general arrangement of the three primary loop feeders, is also shown.

Oil Circuit Breakers. The oil circuit breakers which are installed in the transformer vaults for sectionalizing purposes in case of faults in the primary feeder are rated at 15,000-volt, 400-amperes, with an interrupting

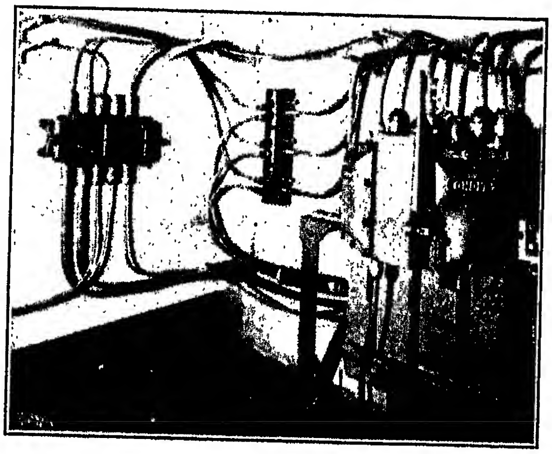


Fig. 3—Typical Vault Showing Installation of Condit Oil Circuit Breaker

capacity of approximately 20,000 amperes at 4000 volts. The maximum short-circuit current in case of a fault on a primary feeder is about 10,000 amperes. Figs. 3 and 4 show the two types of oil circuit breakers used.

Each oil circuit breaker contains six bushing type current transformers, three on each side, with a ratio of 60 to 1. The breaker also has two five-ampere trip coils. The use of these auxiliaries is explained in a later paragraph describing the pilot wire relay circuit.

Because of the secondary network a transformer bank can be disconnected from the system at any time without jeopardizing the service. By taking advantage of this situation the number of oil circuit breakers in each ring feeder has been reduced to a minimum by allowing one transformer bank to be cut out of service in case of primary feeder trouble somewhere in the ring. Fig. 2 shows clearly the general plan used, and indicates that on any one ring feeder, those vaults with transformers which supply a secondary network have a breaker in all vaults except one. The reason for this one exception is readily apparent from the fact that the substation breakers on the two ends of the ring feeder are controlled by the pilot wire relay circuit and operate as a part of the underground system. Referring again to Fig. 2, a vault is shown having two breakers. This becomes necessary only in cases where those vaults supplying isolated loads are at some distance from one another, and for that reason it is not expedient to network their secondary circuits. Two breakers are then required to give complete reliability to the loads being served. However, as other vaults are constructed and the distances between vaults shortened, the secondary circuits in the isolated cases can be connected into a network and one breaker removed from each vault to give the same conditions of operation as that obtained in the general network plan. As will be seen, the layout reduces materially the investment costs per feeder and at the same time does not jeopardize the service being supplied.

Primary Junction Boxes. Two types of primary boxes are in use, one being a three-phase, four-way, and the other being a single-phase, four-way. In either type, two of the four-ways are used for the incoming and outgoing feeder, one is for the transformer tap leads and the fourth is a spare.

The single-phase type is shown in Fig. 3, mounted directly to the left of the oil circuit breaker. This type of box is oil-filled. The arrangement is such that the cables can be easily removed from the box. If a section of cable is to be taken out of service for repairs the ends can be removed from the box and properly shorted and grounded. In the three-phase box the same can be accomplished, not by removing the cables, however, but by removing disconnecting bars located in the box and then applying to the cable terminal a suitable short-circuiting and grounding cable.

Transformers. The transformers are standard type, single-phase, 2400-120/240 volts with two, five per cent taps, giving 18, 19, and 20 to 1 ratio. Standard reactance of approximately 4.3 per cent is used. The sizes used are 50 kv-a., 100 kv-a., and 150 kv-a. Fig. 5 shows a typical installation of a bank of three 100-kv-a.

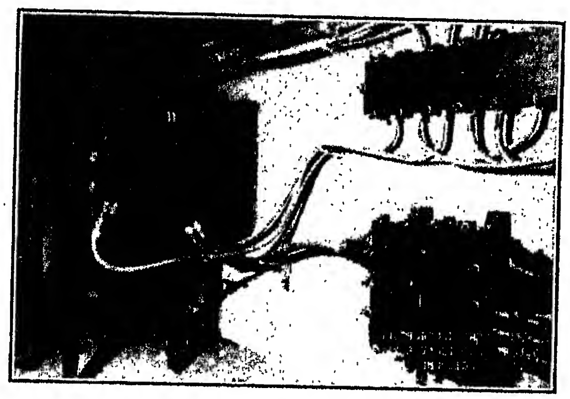


Fig. 4—Typical Vault Showing Installation of General Electric Oil Circuit Breaker

transformers. A 6000 to 5 ratio current transformer placed on one of the secondary leads is located inside the tank of each transformer and is used as a part of the pilot wire relay scheme as described later. The transformers are Y-Y connected. The Y point of the high-voltage and low-voltage windings are connected together inside of the case. The secondary neutral is then brought out of each transformer of the three-phase bank and connected to the neutral of the secondary network, which is grounded only by being connected at

many points to the d-c. Edison neutral. The Edison neutral consists of an extensive grounding grid composed of 1,000,000-cir. mil, paper-insulated, lead-covered cable to which the 500,000-cir. mil neutral secondary mains are connected. This grid has but one earth connection which is located at the substation. The connection from grid to earth is through seven 1,000,000-cir. mil, paper-insulated, lead-covered cables, thus forming a very substantial ground for the a-c. network.

In the connection of transformers to a network system they are of necessity operated in parallel and it therefore

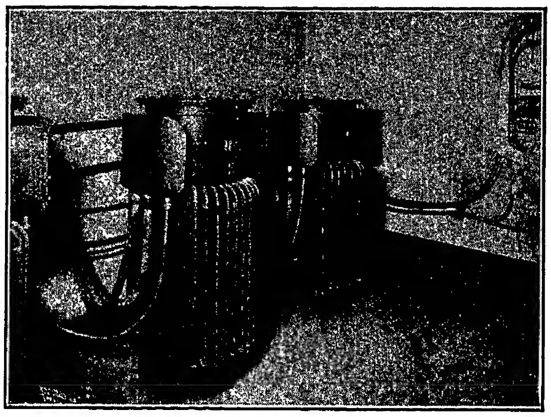


FIG. 5—TYPICAL INSTALLATION OF THREE 100-KV-A. TRANSFORMERS

The small cable entering the low-voltage terminal compartment contains the current transformer secondary leads.

is of great importance that the impedance of the transformers and connecting tie cables be studied with a view that the transformers, as nearly as possible, share the loads on the network. To give the best operation, the impedance of the transformers should be somewhat higher than the impedance of the secondary circuit between the transformers. Although the secondary circuit is of high reactance due to the cables being placed in separate ducts, it was felt that the standard reactance transformers were justified for use on the system, first, from the point of view of voltage regulation and second, that the transformers in the network would at this time be generally underloaded, thereby making the standard reactance transformer suitable. As the network grows and areas in more densely loaded sections are changed over to a-c. operation, surveys of the load division will be made and additional reactance, through the use of cable type reactors, placed in the circuits where required.

Secondary Junction Boxes and Fuses. The transformer secondaries are fused to the mains by open, link-type copper fuses mounted in a water-tight box shown in Fig. 6. The secondary leads from the fuse box in the transformer vault are run in a duct line to the nearest manhole where they enter single-phase, five-way boxes for connection to the mains. Copper strips are used for connecting or disconnecting the secondary mains in these boxes. The boxes are used instead of making up solid wiped joints because it was felt that under certain conditions of operation or in case of severe trouble, sectionalizing at certain positions in the network would be of considerable value.

Secondary Cable. The mains are 500,000-cir. mil, single conductor cables and are installed in separate ducts. The mains, which had been in use on the Edison three-wire system, were used as installed and the fourth conductor was added to give the third phase. The neutral of the former d-c. system was made the neutral of the a-c. system. Because the existing d-c. cables were used the installation of all the conductors in one duct to get advantage of lower reactance or to economize on duct space, was not resorted to, especially in view of the large amount of labor involved in pulling out the three old cables and pulling them back into one duct with the fourth cable. It was also felt that considerable advantage was secured in having each single conductor cable in a separate duct, thereby reducing to a considerable degree the possibility of copper-to-copper short circuits, which for the cables as large as 500,000 cir. mils may be difficult to burn clear and thereby cause serious damage to the cables.

The size of ducts and the relative arrangement of the secondary network cables is indicated by the sectional view in Fig. 1B.

The power supply from transformers to the secondary

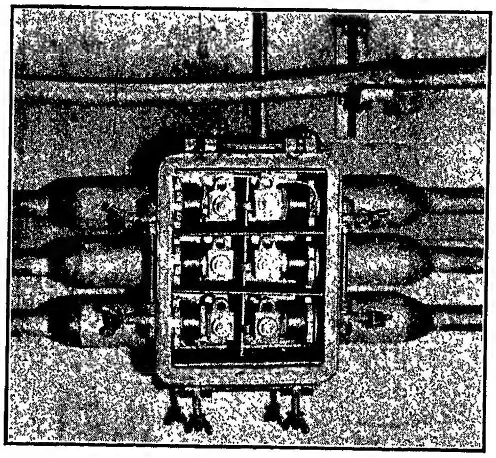


FIG. 6—SECONDARY FUSE BOX WITH COVER REMOVED

mains in the manholes is through 1,000,000-cir. mil, paper-insulated, lead-covered cable for 50- and 100-kv-a. transformers and 2,000,000-cir. mil for 150-kv-a. transformers.

Trouble from sheath currents in single conductor secondaries has not been encountered up to this time. Evidence of such currents will be watched as the demand on the system increases and remedial measures will be taken where they become objectionable.

Control (Pilot Wire) Cable. The control cable for the pilot wire relay circuit consists of a three-conductor, No. 8, seven-strand, 600-volt rubber-insulated, lead-

covered cable. This cable and the signal cable described below are placed together in the same duct and follow, in general, the route of the primary circuit. They enter each transformer vault where connections are made to the auxiliary equipment of the oil circuit breakers and transformers through a specially designed junction box.

Signal Cable. The signal cable is for giving indications at the substation as to the oil circuit breaker positions. This cable consists of four-, eight-, and nineteen-conductor lead-covered cables. Each conductor is No. 12, nineteen-strand, 600-volt, rubber-insulated.

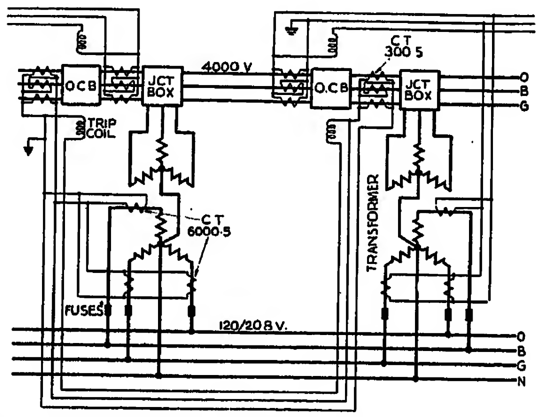


FIG. 7—PILOT-WIRE RELAY CONNECTION DIAGRAM

The circuits for the indications are supplied from a 125-volt d-c. bus in the substation. One common wire in the signal cables enters each vault so that this wire and the grounded side of the 125-volt d-c. circuit forms a telephone circuit which can be used to communicate between any two vaults or between any vault and the supply substation. It was found that during the installation of the system much time was saved in having telephone communication between various vaults. Portable telephones are used. It is anticipated that the portable telephones will be of real value in the job of maintaining and operating the system.

Pilot Wire Relays and Fuse Protection. The connections used in the pilot wire relay scheme are shown in Fig. 7. This scheme of connections was proposed by Mr. Baughn and it is thought that it differs from any scheme formerly used in that the current transformer secondary on the middle phase, is, in all instances, reversed with respect to the other two current transformers.

Assuming balanced three-phase current in the primary, the reversal of one current transformer secondary causes the vector sum of the secondary currents to be twice the current in any one secondary. The vector sum of the currents circulates continuously through the pilot wires and the two groups of current transformers in series. Two trip coils, one in each of the circuit breakers at either end of the primary feeder section, are connected in series by means of a third wire and are connected to two points in the pilot wire circuit, which are at the same potential above ground under normal conditions. Consequently, no current can flow in the trip coils as long as there is no fault in the primary cable included in the pilot wire relay section.

The current transformers in the secondary leads of the power transformers are also connected in a similar manner and the resultant current added to the currents from the current transformers in the primary feeder oil circuit breakers. This is done in order that faults or large loads on the low side of the transformers will not unbalance the pilot wire relaying to such an extent as to cause the circuit breakers to be opened.

The advantage of having one current transformer reversed with respect to the other two is that protection is secured against three-phase faults and also single-phase faults between the phase having the reversed current transformer and either of the other two phases, as well as faults to ground which latter is the only protection secured with this type of connection if one current transformer is not reversed. The only possible fault which this scheme does not protect against is a short circuit between the two phases which do not have the reversed current transformers. However, a fault of this kind will quickly involve either the other phase or ground and cause the breakers to be opened.

A further advantage of this connection is that there is no current through the trip coils, except when a fault occurs within the section protected, no matter how much resistance the pilot wires may have. This allows the use of a fairly small size pilot wire and places

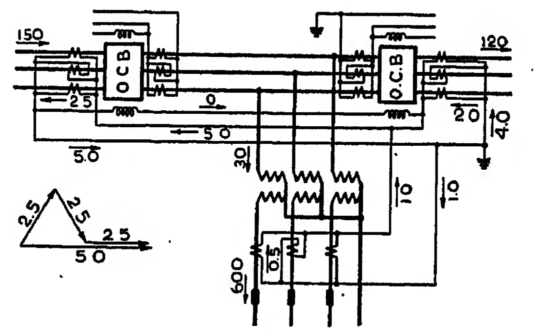


FIG. 8—WIRING DIAGRAM SHOWING CURRENTS IN PILOT WIRES UNDER NORMAL CONDITIONS

no limit on the length of section of cable which can be protected.

When a fault occurs in the high-voltage feeder or in a transformer, current is fed into the fault from both ends of the high-voltage loop feeder and from the low-voltage network. Under this condition the currents in the pilot wires oppose each other and the trip coil circuit provides the only path for these currents. The oil circuit breakers are therefore opened instantly, clearing the fault from the high-voltage feeder. The low-voltage network continues to feed power through the one bank of transformers connected to the section

of cable in which the fault occurred, until the fuse in the low-voltage side of the transformer is blown.

Fig. 8 shows the currents in the power cables and pilot wire circuits under normal conditions for an assumed load of 150 amperes per phase in the high-voltage feeder and 30 amperes per phase in the primary of the transformer bank. Fig. 9 shows the conditions under an assumed three-phase short circuit in the length of cable included in the section of pilot wire relay pro-

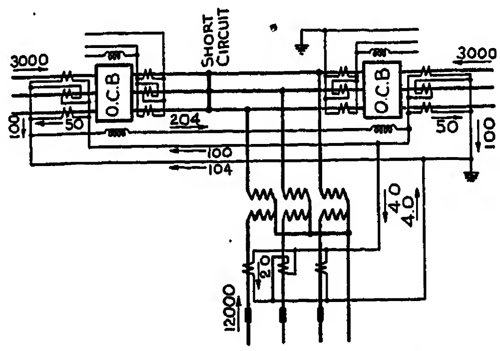


Fig. 9—Wiring Diagram Showing Currents in Pilot Wires under Short-Circuit Conditions

tection shown in the diagram. The values of current shown are assumed for illustration purposes only.

The size of the copper link fuses in the transformer banks varies from 800 to 1500 amperes, rated capacity depending on the size of the transformer and the distance from adjacent vaults. The sizes were chosen

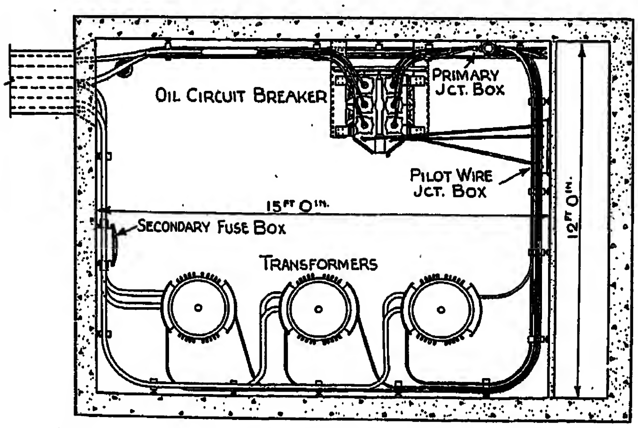


Fig. 10—Plan of Typical Transformer Vault

so that the fuses on the transformers connected to the section of cable on which the fault occurs will be blown in from one-half to three seconds. On the other hand the fuses on the transformers which are supplying the power fed back by the network into the primary fault will not be blown in less than ten times as long, because under all conditions there will be at least three transformer banks supplying the current.

A fault on the secondary mains or services will be burned clear. The fuses on the bank of transformers nearest the secondary fault may be blown, but this will cause a still greater reduction of voltage and assist in extinguishing the arc.

Metering. Single-phase meters are used on small two-wire, 120-volt services or on small two-wire, 208-volt motor or heating load.

Three-phase, three-wire, two-element meters are used on all three-phase, 208-volt power or on all three-wire, 120-volt lighting load or mixed load of lighting and single-phase power.

Three-phase, four-wire, three-element meters are used on mixed lighting and three-phase power.

On those classes of loads where a measurement of the demand is required, a single-phase demand meter is used for three-phase power, two for three-wire, 120/208 lighting and single-phase power, and three for three-phase, four-wire mixed load. On installations of 100 kv-a. or more, one graphic kv-a. meter is used.

Services. All d-c. services which had been supplying a larger motor than three hp. were changed to four-wire, three-phase. This required that an additional wire be added to the service connection and in order to expe-

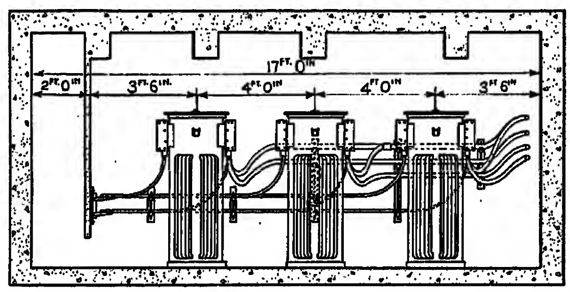


Fig. 11—Sectional Elevation of Transformer Vault Showing Arrangement of Transformers

dite the work on the final change-over of any certain district, these services were made ready beforehand. Practically all services were in iron pipes and in many instances these had to be changed to larger size to accommodate the four cables. In the cases of large services, however, separate fiber ducts were placed, one for each cable.

Very little changing was necessary in the interior wiring of the individual buildings to accommodate the new service.

Transformer Vaults. The transformer vaults have been placed in the street, it having been found impractical to place them in the areaways under the sidewalks.

The vaults are of two general sizes: one 7 ft. high, 12 ft. wide, and 17 ft. long, where one oil circuit breaker is used and one 7 ft. high, 12 ft. wide, and 21 ft. long, where two oil circuit breakers are used. The two oil circuit breakers are installed in vaults only where radial secondaries are supplied. In some cases a vault of special dimensions is required because of the congested conditions in the street.

Figs. 10, 11, and 12 show the vault outline and the arrangement of the electrical equipment.

Natural ventilation is provided and is accomplished

by means of steel grates in the roof at each end of the vault. The proper chimmey action is provided by carrying the inlet on one end to approximately 12 in. from the floor. This is clearly shown in Fig. 12. The effective opening of the grates at each end is 900 sq. in., which is calculated to take care of a 450-kv-a. bank of subway transformers.

In order to provide entrance for equipment, the manhole is made with a 40-in. clear opening. A cover for such an opening would be extremely heavy to handle so it has been made in two parts, an outer

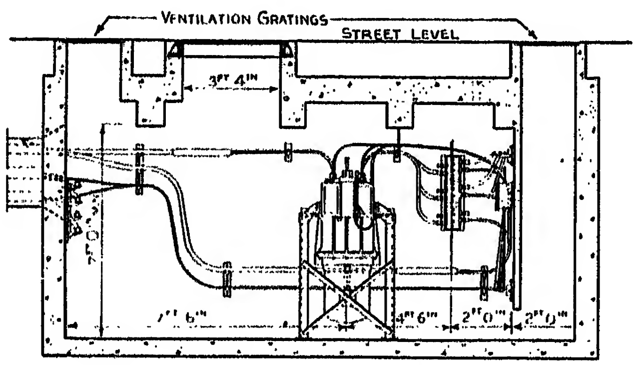


FIG. 12—SECTIONAL ELEVATION OF TRANSFORMER VAULT SHOWING OIL CIRCUIT BREAKER, JUNCTION BOXES, AND ARRANGEMENT FOR VENTILATION

annular ring with a 26-in. central hole and a 26-in. standard manhole cover which can be easily handled by one man. The ring and cover are of cast steel manufactured by the electric furnace process. The roof of all transformer vaults, including manhole cover and ventilating grids, was designed for a concentrated load of 30,000 lb. placed at any point on the roof.

Wherever possible the vaults are drained to the sewer through suitable traps; where no sewer connection is possible a sump is provided.

There are two outlets provided for lighting each vault, the wiring being in conduit and connected onto the outgoing side of the secondary fuse box.

Emergency Substation. Fig. 13 shows a portable type emergency substation to be used in connection with the a-c. system for emergency supply in case of failure of subway transformer banks whose secondaries have not as yet been tied into the network system.

The substation consists of three 100 kv-a. distribution transformers complete with an oil circuit breaker and sufficient lengths of primary and secondary cables to drop into the vaults and connect to the junction boxes. These cables are supplied with the proper terminals so the connections can be made to the junction boxes in a minimum of time. Each cable is marked with a color scheme identical to that followed out in marking the cables of the underground system. This eliminates the necessity of phasing out and the attendant confusion usually prevalent when making up hasty connections.

TESTS UNDER FAULT CONDITIONS

After the network had been in operation for some time, without any trouble developing, it was decided to test its operation under conditions of short circuit by placing artificial grounds and short circuits on both the primary and secondary cables at a time when the results could be observed.

Tests on Primary Cable. The first test on primary cable was made by connecting to the primary feeder through a temporary oil circuit breaker a short piece of three-conductor, 4000-volt cable, with one of the conductors grounded to its lead sheath. When the temporary breaker was closed the subway primary breakers on each side of the ground opened instantly, clearing the fault from the primary feeder. The test was made at the edge of the network where the vaults are far apart and the transformer banks installed in each vault had a capacity of 150 kv-a.. The feed-back of current from the secondary network was 1800 amperes, which was not sufficient to blow the 1000-ampere fuses which were in use. The fuses have since been changed to 800 amperes. The secondary voltage was reduced from 123 volts to 20 volts at the vault where the test was made and from 123 volts to 110 volts at a vault 682 ft. away.

The second test was made at the same location and

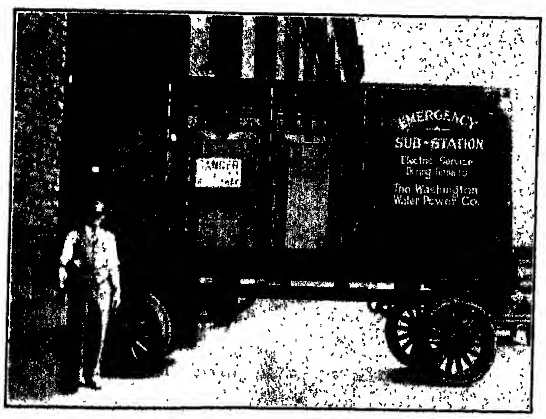


FIG. 13—PORTABLE TYPE EMERGENCY SUBSTATION

consisted of placing a three-phase short circuit on the primary feeder. The subway breakers operated satisfactorily and the feed-back of current from the network was 3000 amperes per phase, which blew the 1000-ampere fuses in 3.25 seconds, completely isolating the fault. The secondary voltages at the two vaults mentioned under the first test were 20 volts and 101 volts respectively.

The three-phase short-circuit test was repeated at another location where the vaults are closer together and the transformer banks larger. The pilot wire relaying worked perfectly, and opened the subway oil circuit breakers instantly. The feed-back from the network was about 7000 amperes and blew the 1500-ampere fuses in 2.5 seconds on the first trial and 2.0 seconds on

the second trial. The secondary voltages at the vault under test and a vault 500 ft. away were reduced to 35 volts and 95 volts respectively.

Tests on Secondary Cables. The first test on the secondary cables consisted of taking a short length of 500,000 cir. mil cable and driving a nail through the lead sheath into the copper. This piece of cable was attached through a temporary breaker to one phase of the secondary mains. The test was made at a point 336 ft. from one vault, 346 ft. from a second, and 867 ft. from a third, each having three 50-kv-a. transformers installed. The cable with the nail in place was put in an 8-ft. length of fiber conduit. When the temporary breaker was closed there was a slight explosion accompanied by a puff of smoke, after which the short circuit immediately cleared. An examination of the cable showed the lead had been burned back about 1/16 in. from all sides of the nail.

The second test consisting of a copper-to-copper short circuit at 208 volts, was made by baring the ends of two No. 2 paper-insulated, lead-covered, 1500-volt cables for a distance of three inches, laying them side by side, and binding them together by means of a copper wire. The ends were then slipped about half way through an 8-ft. length of conduit. The power was applied and at the same instant there were two violent explosions separated by a fraction of a second. The short circuit was cleared in approximately one second. Examination showed the copper to be burned so that the two cables were separated by about ⅛ in.

A third test was made in a manner similar to the second test, except that two No. 00 cables were used and that a small iron washer was placed between the ends of the cables and bound in place with tape. Upon applying the power, the results were found to be quite similar to those obtained in the test on the No. 2 copper cables except that the short circuit was somewhat longer in clearing, the time being about one second.

A fourth test was made using two 250,000-cir. mil cables prepared the same as in the third test. When the power was applied the short circuit held for about one second, and then an explosion cleared the fault in approximately two seconds. The voltage across the phase used in testing dropped from 215 volts to about 150 volts at the two vaults nearer the point of test, which indicated that these two vaults supplied about 1600 amperes each to the fault.

A fifth test was made using two 250,000-cir. mil cables prepared in the same manner as in the fourth test, but connected to the mains at a point about midway between two 300-kv-a. banks of transformers in vaults 500 ft. apart. In this case the short circuit was cleared with one violent explosion in considerably less than one second.

In no case did the secondary fuses show signs of heating during the secondary short-circuit test.

The tests which were made seem to indicate that if trouble does occur, the system will operate as designed.

Voltage Regulation

The line drop compensators on the induction regulators are set to compensate to the low-voltage side of the transformer at approximately the center of the loop. No provision has been made for cross-connecting the compensators on the different feeders. The operation of the induction regulators has been entirely satisfactory, without any tendency for the regulators on the different feeders to buck each other.

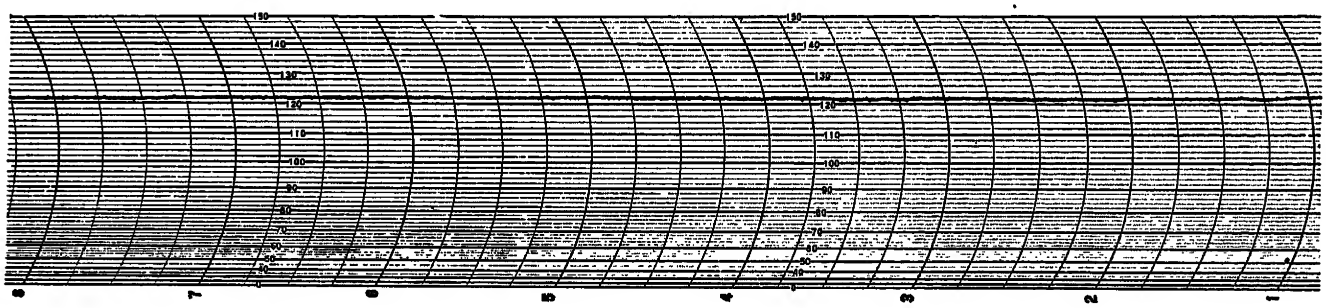


Fig. 14—Graphic Voltmeter Chart Taken at the Service Switch of Typical Customer with Combined Power and Light Load

Tests made by graphic voltmeters show that the voltage at the customer's service switch normally varies from 122 volts to 120 volts and that there are no sudden variations of sufficient magnitude to cause flickering of lights except in one instance where an a-c. elevator motor of 20 hp. on the end of a service 95 ft. long attached midway between two vaults 670 ft. apart caused a fluctuation of 3 to 4 volts.

Sections of two charts, one taken at the service switch of a typical customer having combined light and power load and the other at the customer with the elevator motor referred to above, are shown in Figs. 14 and 15.

In order to avoid lamp flicker, the maximum starting current taken by any motor which may be connected to the network is limited to the amount which will cause a drop of three volts at the customer's service switch. Carefully prepared tables applicable to the particular size of mains, spacing of cables and reactance of transformers used in Spokane, but based on the general

discussion of lamp flicker by Mr. D. K. Blake[3] are used to predetermine the maximum allowable size of motor.

General Procedure in Change-Over from Direct Current to Alternating Current

Customer Consideration. Some time prior to the change-over, records were obtained covering the amount and condition of the customer's d-c. equipment. The customer was then advised of the change which was anticipated and of the approximate date the change in service would be made. He was also asked to have estimates made by an electrical contractor on the cost of replacing his d-c. equipment with a-c. equipment, and the cost of making any necessary changes in the wiring and service entrance facilities.

Arrangements were made whereby the contractor furnished the power company with a copy of all bids which were submitted to clients. These bids were carefully checked and then used as a basis for drawing up an agreement between the power company and the customer. This agreement provided for the changes which were necessary in each individual case with a definite statement as to the part of the cost which would be paid for by the power company.

A salvage was allowed on the old apparatus and all d-c. equipment removed from the customer's premises became the property of the power company.

A number of special cases arose during the process of the negotiations which called for other considerations than those stated above, but as a general rule the procedure was as outlined.

Equipment Involved in Change-Over. The d-c. motors on the passenger elevators, serving some of the office buildings and hotels, were not changed. The power supply to these motors was provided by means of motor-generator sets installed on the customer's premises.

A-c. motors were substituted for the d-c. motors on all freight elevators and on passenger elevators in those office buildings and hotels where motor-generator sets were not installed.

3. *General Elec. Rev.*, April 1928, p. 186.

Some of the heating and cooking equipment used in the area was found equipped with 230- and 240-volt elements. This equipment was taken care of by the installation of auto-transformers, which raised the 208-volt service to 228 volts.

No operating difficulties have been encountered in customers' equipment up to this time. All motors have operated satisfactorily on 208 volts.

Plan and Schedule for Making Change from D-C. to A-C. In order to inconvenience the customer the least possible amount during the change-over, plans were carefully laid out and a complete schedule of the changes arranged. A block or two, depending on the density of the load, was changed over at a time. The plan required the closest cooperation between the customers, contractors, and the power company.

In some cases it was necessary to maintain a temporary d-c. service in certain sections which were changed to the a-c. service. Such cases were rare, however, but where necessary it was found that some d-c. feeder which had previously fed the d-c. network could be utilized for the service without interfering with the rest of the work.

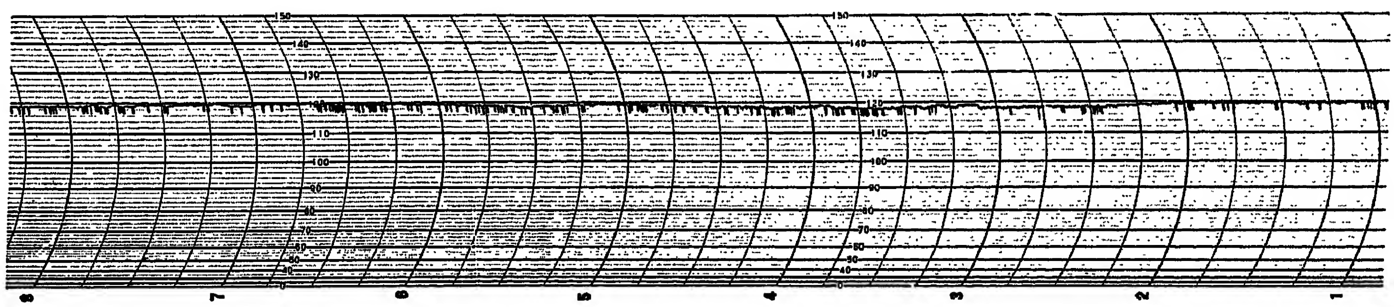


Fig. 15—Graphic Voltmeter Chart Taken at the Service Switch of Customer Having 20-Hp., A-c. Elevator Motor on the End of an Exceptionally Long Service

The total number of customers involved in the 1928 change-over was approximately 700.

Conclusions

There have been no difficulties encountered on the system since its installation. The operation to date has been one hundred per cent. There have been no complaints because of low voltage or unsatisfactory motor performance.

In order to create some sort of a check on the system and its operation under fault conditions, numerous tests were run which have indicated that the system functions perfectly on the worst type of fault.

The fuse operation proves its complete dependability and can be relied upon to sectionalize the system properly when conditions exist for its predetermined action. The pilot wire control also gives complete assurance of its service in sectionalizing primary faults. The very small reduction in power supply to the secondary network due to a primary fault eliminating only

one transformer bank is a distinct value to the service rendered.

The tests simulating copper-to-copper faults in the secondary cables indicate that the cables will burn clear with very little disturbance to the network.

In general, there is every reason to believe that the universal type of a-c. network without network protectors, as now installed in Spokane, will continue to prove its worth as a means of supplying energy to one of the highest types of electric service.

Discussion

V. B. Wilfley: Many engineers are strong advocates of the distribution system employing radial feeders and interconnected three-phase, four-wire secondaries with network protectors for the general case of the normal large city. This stand on their part has been taken only after considerable study of all types of systems and after observing this particular type of system in operation in about 40 cities.

The fact that the Washington Water Power Company engineers have adopted a system using ring feeders and fuses instead of network protectors should certainly not be taken to mean that this system will be desirable in other cities. We feel certain that Mr. Gamble had no such idea in mind in the presentation of his paper.

If Mr. Gamble has such figures available, we should be interested in knowing the approximate difference in cost per kv-a. (both original and operating costs) for the two systems as applied to his case; also, whether the additions of network protectors or low-tension breakers to the present scheme would make the ring feeder system the more costly one.

Our suggestion would be that additional tests should be made in order to check the operation fully. I do not recall that a test was made involving a secondary fault near a transformer bank. It can certainly be expected that the transformer fuses would blow for this case, which to my mind, would lessen the possibility of burning the fault clear. A network protector would, of course, function satisfactorily and no trip to the vault would be necessary to replace fuses. Such faults may be infrequent now but they may be expected in greater numbers as the system grows old.

The pilot-wire scheme is particularly interesting and Mr. Baughn is to be complimented on his originality. As pointed out, only three pilot wires are required and only two trip coils per breaker. Its weakness is its inability to function in the case of a particular phase-to-phase feeder fault until that fault has developed into either a phase-to-ground or a three-phase fault. I am inclined to agree with Mr. Gamble that such a development may take place provided the time and energy conditions are right. but these are uncertain factors.

Let us assume that such a phase-to-phase fault occurs on the Spokane system near a vault. With the pilot-wire system inoperative, it can be expected that the main substation breaker will open, clearing the feeder entirely from any feed except that from the network. The fuses on the nearest bank will blow as for any other feeder fault provided the fault is near the bank, and later the fuses on the banks in adjacent vaults may be expected to blow unless fused fairly high. If they do, then energy available for developing the fault into the type which can be cleared is very small and low voltage will exist over the network for a considerable length of time. It is my opinion that it would be worth while to arrange a test involving a specially faulted piece of feeder cable to check the resulting action. Such a test would be difficult to bring about under actual conditions but would certainly be desirable.

If we consider the action of network protectors in the above picture, matters are worse as all protectors on the faulty feeder would open leaving the faulty feeder entirely out of service, making it necessary to segregate the faulty section by hand before putting the feeder back in service. I believe Mr. Gamble has considered the idea of low-voltage switches which would be operated by the feeder pilot-wire circuit. This would give much better operating characteristics but would really be equivalent to a network protector system without many of its advantages, such as reclosing automatically, efficient operation of transformers, etc. I am wondering what effect the additional cost of low-tension switches would have on a cost comparison as mentioned previously.

Was the *Z* pilot wire connection considered? This involves five wires and four trip coils per breaker but gives complete protection.

Another question: What was the principal reason for the selection of *Y* transformer connections? It fits in well with a pilot-wire system but I am wondering if any other reason existed. It is interesting and gratifying to note that Mr. Gamble and his associates seemingly had no fear regarding the use of the odd voltages involved in a three-phase, four-wire secondary. This is one of the principal causes of hestitation in adopting the system in many cases.

H. Richter: At the outset this paper states that a general survey of the downtown distribution system was made in 1923, and the context leads one to assume that the decision on the type of a-c. system described was made soon thereafter, or some time in 1924. It will be recalled that there was only one a-c. automatic network system, of small extent, then in operation. Starting with a high percentage of failures in operation, the automatic network protectors had yet to be proved as reliable parts of a distribution system, whereas oil circuit breakers with differential pilot-wire control, and fuses, were common everyday tools.

It is therefore readily evident that for that time and the particular conditions in Spokane the network system chosen there was as good as any then known. That it will probably give satisfactory service in Spokane for some years is also apparent. But subsequent study of this type of system and the wide experience with the radial-feed automatic network system bring the conviction that the latter has now been proved superior to the former for the heavily loaded underground areas in almost all cities.

The paper says the system was so chosen that no part or element had not been tried out in service. The first difference between the two types of systems, then, is a matter of confidence. But today loads that are among the most important and exacting in the country, such as in New York City, depend entirely on automatic network protectors, and this system is being installed where direct current with storage batteries used to be the rule. On the other hand, several companies that formerly applied fuses in the low-voltage leads of the transformers for network protection have abandoned them after several years of experience, due to minor troubles, severe outages, or to a realization of the advantages of the automatic protectors.

Forty operating companies have put their confidence in the radial-feed automatic network system since the first one was started in 1922, the increase in the number having been 16 during the past year; but after the introduction of the first loop-feed fused network five years ago there has been only the one addition, in Spokane.

It may be noted that in 1924 the star-connected combined light and power scheme chosen for the secondaries of the Spokane network system was considered by many operating engineers to be just as experimental as the automatic network protectors. Developments since then have justified the confidence of the small group of men who in the early days had faith that both innovations would be successful.

Fig. 1A in the paper shows a railway cutting through areas 2 and 3, and in Fig. 1B the transformer installations are clearly separated into two groups. This special condition may have

accounted for the cost of the loop-feed network being somewhat lower. But it would be hazardous to generalize along this line. Even where conditions may closely parallel those in Spokane the latest methods of designing the radial-feed automatic network system and the improvements in network protectors may throw the difference in cost against the loop-feed fused network system.

There is in addition some doubt that the loop-feed network is cheaper than the radial-feed network for an important isolated load away from the main network. Suppose such a load were an average of 2000 ft. from the two nearest transformer banks connected to the network mesh. As these banks are supplied from two different feeders in the radial-feed system, two laterals each about 2000 ft. can be run out from these installations to the isolated load and the copper section might be tapered to suit the size of the load. With the loop feeder the length of cable out from the main network and back would be very little less than the same 4000 ft., and the cable size would be identical with that throughout the extent of the feeder. In addition there would be the pilot cable, so that the cost of cable would be greater for the loop-feeder method.

At the isolated load in the loop scheme there are two high-rupture-capacity high-voltage oil circuit breakers, and primary and pilot-wire junction boxes. With radial feeders there might be an oil circuit breaker on each of the two incoming lines, but they would be of low rupture capacity; and an automatic throw-over panel to control connection of the transformer bank to the emergency feeder when the preferred feeder trips out. Or, if the load be important enough to require a standby transformer bank or one bank for light and another for power, the two radial feeders could be connected directly to the two banks, an automatic network protector installed in the low-voltage leads of each bank and these leads tied together through a small reactor to form an isolated network. Neither of these radial-feed methods is likely to cost more, as a whole, than the loop feed and the network protectors would give more reliable service in case of transformer trouble. There appears to be a growing tendency throughout the country to treat important isolated loads in this manner.

The primary junction boxes described are omitted in the radial-feed automatic network system because there is no need to make changes in the primary cable connections in a hurry at the time of a fault or for extensions. Ample capacity is allowed to carry the peak load indefinitely with any feeder out.

Reference is made to secondary junction boxes for sectionalizing the secondary network in case of severe trouble. Some companies operating automatic network systems also started with them, mostly because the boxes were inherited from the radial secondary system; but in most of the applications they are now largely dispensed with. To make this practicable, care is taken that all transformer banks remain connected to the network on a secondary short circuit to pump every possible ampere into the fault and burn it off quickly.

Such auxiliary equipment as the pilot-wire junction box is, of course, non-existent in the radial-feed automatic network, and the same applies to the pilot and position-indicating cables.

The use of only one regulator (or set) per loop feeder is brought out. Where the feeders are longer than in Spokane, as in the majority of cities, proper voltage regulation may require a regulator in each leg of each loop. There are several examples of this. As each side of the loop must be able to carry the entire load of the feeder should the other side become disconnected at the station, the two regulators are of greater capacity than for radial feeders. This is true even considering the spare capacity that is allowed in the network system for the possibility of one radial feeder out of service.

As regards the single regulator per loop, should it be put out of service during the peak of the year it is likely that the entire loop would have to be shut down. This might result in blowing protective fuses all over the system, causing a complete outage.

Likewise, if there occurred simultaneously a fault in an end section of the loop and a failure of the circuit breaker separating this section from the rest of the loop, the entire loop feeder would go dead. This might be termed too remote a possibility to warrant special precautions but not by engineers who have witnessed similar "impossibilities" come true.

Figs. 3 and 4 show two kinds of subway type high-rupture-capacity oil circuit breakers for sectionalizing the loops. There is now available a third type in which an effort has been made to obtain improvements affecting accessibility, proof against water leakage, safety, and standardization of parts.

Turning now to the protective fuses, experience with networks of all kinds indicates the advantages of clearing the fault current from the system as quickly as possible. The older the cables and apparatus the more important does this become. The paper gives 3.25 seconds as one of the periods required in clearing a primary fault, and for 1800 amperes on the 800-ampere fuse the time would probably be longer. The automatic network protector has the decided advantage of tripping within about 0.4 second on a phase-to-neutral primary short circuit and about 0.25 second if phase-to-phase.

With respect to the failure of the 1000-ampere fuse to blow on 1800 amperes, as described, tests on similar fuses indicate that 2000 amperes would just melt them. Considerably more than this would be needed to clear in a short enough interval of time to come within the safe operating thermal capacity of the transformers. It is thus very doubtful whether the 1800 amperes available would blow the 800-ampere fuse quickly enough under the test conditions assumed.

In designing a radial-feed network system it is the general practise to determine primary and secondary short-circuit current with any feeder out of service for repairs, etc., as this condition may sometimes occur. Likewise in the loop-feed fused network, a transformer bank may be out when a primary fault takes place at an adjacent bank. From the description of the tests it appears that no nearby bank was disconnected. It is easily possible that if one had been, only about 1400 to 1500 amperes might have been obtained instead of 1800 and the 800-ampere fuse would not have blown at all. And so the tests appear to indicate that the fuses might not be dependable in always clearing primary faults. Yet this is one of the fundamental requirements of a network protector.

In the loop-feed fused network the fuses must be reasonably low in rating to blow on primary faults, as already indicated. Should a phase-to-phase short circuit occur on the low-voltage mesh close to a transformer bank, it is almost certain that the fuses at that bank would quickly blow. The resulting sharp decrease in current would make more difficult the completion of the burning-off process, and in some cases might make it impossible. As time went on the fuses at adjacent banks would melt. On some systems that have depended on secondary fuses the whole network has thus become involved, resulting in complete shutdown. As an example, in one city in the South this occurred three different times and then network protectors were substituted for the transformer low-voltage fuses.

It might be doubted that a phase-to-phase short circuit would occur with each secondary cable in a separate duct, as in Spokane. Such faults have occurred in the manhole, however. For instance, on one medium-size a-c. network all three-phase wires on the low-voltage side in a manhole recently became involved in a severe fault.

It would thus have been of value, when the secondary cable burning off tests were made, to establish a short circuit close to a transformer bank, allow the protective fuses at that bank to blow, and determine whether the fault would clear itself under this condition. Otherwise it is not certain that no serious trouble may develop due to failure to burn clear. As severe phase-to-phase as well as minor phase-to-neutral short circuits must be cleared, it would likewise have been valuable to have made phase-

to-phase tests on the 500,000-cir. mil cables as well as on the smaller sizes.

The paper states that the blowing of fuses near a secondary fault assists in extinguishing the arc by reducing the voltage. This may be true but it is so important a matter that it should have exhaustive tests to substantiate it. Even if it were found true, there would still be the large percentage of cases wherein it takes considerable time for the arc to develop. Here the all-important factor is the heating, and this decreases as the square of the current. The reduction of voltage resulting in a decrease of the heating at the point of fault would thus be just the opposite of beneficial.

Although there is a reference to secondary single-conductor cables each in a separate duct as the present practise in Spokane, there is no indication as to the future policy. Three 500,000-cir. mil cables in the same duct improves regulation by reducing the reactance, reduces sheath currents, and saves two to three ducts. The neutral needs no extra ducts as it can be pulled in with the three-phase wires, or made common with the primary neutral or existing d-c. neutral, or buried in the concrete of the duct bank in pouring the concrete. There is a trend of thought toward eliminating the lead sheath on network secondary cables; this will be interesting as regards cutting down the developing of copper-to-copper faults when three single-conductor cables are in the same duct. The experience of operating companies shows, however, that where ordinary care is taken in the design and construction of an automatic network system, such faults on 500,000-cir. mil lead-covered cables will burn clear every time.

Considering the Spokane system as a whole, it is only natural that no trouble should be encountered with a new underground system. The real test will come after a few years. At that time the basic principles of simplicity of system, low-voltage switching, instantaneous isolation of faults, automatic reclosing of network protective equipment, etc., typical of the radial-feed automatic network system, will probably prove preferable. It is because of such considerations that over 95 per cent of the companies that have adopted a-c. networks have chosen this particular system.

As an example of what the 40 companies think of the automatic network system, the following report is taken at random: "Since this network was started under automatic control there has not been a single interruption in the district served, except one due to a general system shutdown. The operation of the apparatus is practically perfect." This network is in a foreign country; it has a peak of about 5000 kv-a. and has been in operation over a year.

One system with several years of experience gets 0.1 per cent operating failures on all network protectors together. Compare this with the average of about 1 per cent for protective relays and oil circuit breakers in many generating stations and substations and the reliability of the network protectors can no longer be questioned. Hence, if there was a need for the loop-feed fused system it has passed. In addition to the advantages inherent in the radial-feed automatic network system it also carries with it such promising improvements as operating synchronized at the load. It is rapidly becoming the standard for heavily loaded applications.

L. R. Gamble: I rather hesitate to say much on the question of costs. We have some figures, but as they are more or less tentative at the present time I should prefer not to have them go in the record now. However, in analyzing the loop-feeder plan, and the radial-feeder plan for the Spokane underground system, we found that the loop feeder would be the least in cost by a considerable amount. This was one of the primary reasons for adopting the loop type of feeder.

In regard to the question asked about fuses blowing with a short circuit occurring near a vault: The tests indicated, of course, that the fuses did not blow. However, our tests were made about halfway between vaults and represented practically the same conditions for low voltage as a fault near a transformer bank on which the fuses had blown. I think that the test is representative of a short circuit on the secondary mains at any location.

The Z connection was brought up. Such a connection was considered, but we did not use it because it required more conductors in the control cable. The Y-Y transformer connection was provided, but not on account of any relay consideration. Such a connection has been more or less normal practise with various companies throughout the country and it seems to be working out very satisfactorily, especially where the connection is such that a circuit is provided for the third harmonic. Our 4000-volt supply is through a 13,000-volt transformer bank which is delta-connected on the high side.

In regard to the ventilation system, we found that in order to properly dissipate the heat from a 450-kv-a. bank of transformers it would be necessary to have approximately 900 sq. ft. of ventilating area. This area was provided by means of gratings at each end of the vault, and chimney action secured by building a curtain wall at one end of the vault extending from the ceiling to approximately 18 in. from the floor.

We are running tests now to determine the efficiency of the ventilating scheme. I am sorry we do not have the results to report now.

We wanted to get away from forced ventilation because we desired the vaults to be as simple in operation as possible. We didn't want fans or anything of that nature which would require maintenance.

In replying to some of the questions brought out in Mr. Richter's discussion, I shall attempt to answer them in the order in which they were asked.

The decision on the type of a-c. system as described in our paper was made in 1926, about three years after the general survey of the downtown distribution was made. At that time it was apparent that the operating characteristics of the network protector were still far from what would be desired and much hesitation was felt in its use where service reliability was paramount. In recent papers before the Institute we can still find reports of many faulty operations of the network protector, showing there are still some features in their design which must receive further thought and study to make them more reliable. I certainly agree with Mr. Richter that the difference between the two types of systems is a matter of confidence.

It may be a fact that many companies are abandoning the low-voltage fuses for network protection, but it is only natural since the particular combinations of circuits on which such fuses were applied made their use unsatisfactory.

It is very gratifying to realize that so much confidence is at last being placed in the network protector and that 16 companies have resigned themselves to its use in the past year; such wide application will, no doubt, tend to bring the protector into perfection more rapidly.

It is a fact that the railway shown running through Areas 2 and 3 on Fig. 1A had some influence in making the loop feeder the lower in cost. Nevertheless, later estimates, extending over a period of years, when practically the entire underground system would be changed to alternating current, show the costs of the two types to be about equal. However, in the beginning there was quite a differential in favor of the loop.

The case cited of the cost of serving important isolated loads does not fit the conditions in Spokane. It was found that the cost to serve such loads radially was considerably higher than by means of the loop feeder. The question of transformer reliability I feel can be left out of the picture.

The primary junction box is considered a very convenient piece of equipment because it is a point at which short circuits and grounds can be applied in cases where the primary is being worked upon. The secondary junction boxes, which are mentioned in our paper, are used only at street intersections, mainly

for convenience in making the numerous cable connections and to speed up the work in making the change-over from direct to alternating current. They may also be of some value in emergencies in case of fires, etc., when the network could be split up and service in the effected area could be cut off without seriously interfering with the balance of the network.

Regarding the regulator problem, it is apparent that the situation in Spokane is ideal; the relatively short loop feeders make only one set of regulators necessary for each loop. However, it appears to me that in those cities where the feeders are longer the economics of the situation should be studied to determine whether or not substations cannot be more economically located to make the feeders shorter.

It is a fact that regulating equipment gets out of order at times and to provide for any breakdown a pass-by switch is made available. Also by referring to Fig. 2 of the paper in the "Substation," there are three oil circuit breakers, two at each end of the loop feeder and one connecting the loop to the main bus. An electrical interlock is provided between to the two loop switches and the main breaker, so that any trouble in the auxiliary bus regulator or reactor opens the main breaker and the two loop breakers, and prevents any feedback from the secondary network. It is suggested that the loss of a loop feeder during peak will result in blowing fuses all over the system. This is impossible and with the proper interlacing of feeders no inconvenience should be experienced at all, not even low voltage. Yet I wonder what would happen on a radial-feeder system if at the time one radial feeder was out for repairs, a second one got in trouble, and at the same instant, which is not entirely unlikely, a network protector ceased to function.

The sizes of protective fuses have been worked out by the use of accurate test data. Various locations in the loops require different sizes. Any change in the loop or addition of vaults to the loops requires a complete check of the fuse sizes and perhaps a change of the sizes in the vicinity where alterations are made. With this plan followed up the fuses, beyond a doubt, will give us 100 per cent reliability.

As stated in the paper, one of the tests was made on the outer edge of the network where the load density was extremely small and the distance between vaults very great. This simulated the condition Mr. Richter mentions for the case of a near-by bank being disconnected. Therefore, the adequacy of the fuses to blow where there are larger and more closely spaced transformers is entirely vindicated.

The question of the proper functioning of the fuses in the case of short circuits on the low-voltage network was clearly demonstrated by the tests. The tests as applied in one case simulated again the result of a fuse on a nearby vault blowing and thereby reducing the current to a point where the fault would not clear. We applied the worst condition and the fault cleared without any apparent over-stressing of the fuses. I am not aware of any city in the South having fuse trouble due to short circuits on the secondaries, but if the conditions were as reported there must have been some set-up in their circuits and in size and type of fuses used that were entirely different from the conditions in Spokane.

I am not sure that Mr. Richter understood that all of the copper-to-copper tests were phase-to-phase tests and not phase-to-neutral tests. However, the suggestion that tests using 500,000 cir. mil cables would have been of value is well taken, but time did not permit and it is hoped that some further tests can be made when the opportunity arises.

It is planned to leave the present secondary cables as installed (each in a separate duct); however, future extensions will be made by placing all the three-phase wires in the same duct. Some thought is being given to the use of non-leaded cable, starting first by making use of such cable in service connections.

It is a fact that our system is new and so it is with a large number of the radial type and it is surprising, therefore, that the radial systems have not given a better record. The simplicity of the radial system would, of course, be very evident if the network protector did not have to be considered; otherwise, it seems that the loop feeder is preferable.

I am sorry to see that operating failures of network protectors have been compared with protective relays and oil circuit breakers and not with a pilot-wire scheme with subway-type breakers.

The loop-feed fused system provides unquestionably an adequate service for underground network systems.

High-Voltage Low-Current Fuses and Switches

BY ROY WILKINS[1]

Fellow, A. I. E. E.

Synopsis.—For interruption of small currents at relatively high voltages, fuses and air-break switches are most commonly employed. This paper treats of these devices which are suitable for such service as protection on the transmission lines supplying small blocks of power such as rural lines. The requirements for this service are outlined and a discussion is given of the ability of the devices to meet these requirements.

* * * * *

FROM the beginning of the commercial use of electricity one of the problems has been the interrupting of the flow of current in time of need. This is still, after forty or more years, the major problem in the operation of the transmission networks supplying power throughout the world. On its successful accomplishment depends the continuity of electric service so essential to modern life and industry.

In those parts of the transmission network handling large blocks of power, the economic apportioning of cost allows both a high initial capital outlay and a high maintenance cost, and because of its importance demands the best in research and development that the industry affords, resulting in advanced types of circuit breakers and relays to control them.

On the other hand very small blocks of power, found for instance in rural communities, have economic limitations which limit the amount that may be spent and still expect a reasonable return on the investment. They must be supplied by a moderately high-tension line because of the distances covered, and the efficiency of the lines and transformers corresponds within reasonable limits to those on the major circuits. Circuit-interrupting equipment for this class of service is notably deficient if kept within the usual economic limits, particularly so, since the advent of automatic service restoring equipment now in common use on the low-tension side of the transformers used. The greater portion of such installations now are protected on the high-tension side by fuses of various designs and automatic airbreak switches are employed to a smaller extent.

The second important application of high-tension fuses at the present time is for the protection of potential transformers used as metering equipment. Since it has become almost universal practise to sacrifice the transformer when it gets into trouble and depend on the fuse to clear the system from it, the necessity for very low-current fuses has disappeared and the place filled by a fuse having a rating of from five to ten amperes in series with a resistor. For these conditions present day fuses perform reasonably well.

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Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.

Fuses

The original circuit-interrupting equipment was simply a reduced section of the conductor which opened the circuit by melting. As the demands increased, various alloys melting at lower temperature than the usual conductor were employed. For the use on high-tension circuits, however, the more durable metals are required for sturdy construction.

The melting curves for ideal conditions follow a logarithmic law, and if the time is short enough or the fuse heat-insulated, as for instance sealed in a vacuum, the law holds quite closely for long fuses. For very short sections a correction for heat transfer to the terminals must be made.

Theoretically there is a definite quantity of heat required to melt a given quantity of each metal to be supplied as watt seconds by $I^2 R$ in the fuse. Practically the various indeterminates, such as conduction and radiation, make the calculation of fusing time for a given fuse on a given current very difficult and generally unsatisfactory, so that various empirical or semi-empirical formulas have been proposed similar for instance to:

$$C = K\, d^{3/2}$$

where C = amperes

K = a constant for each metal and

d = the diameter of the fuse

Such formulas were determined empirically for each fuse for given conditions.

Of the more general formulas in common use those having a factor for the fusing time are the most serviceable, for example:

$$t = \frac{0.262\, \pi^2\, d^4\, s\, w}{I^2\, r_0\, \alpha} \log \frac{1 + \alpha\, T_m}{1 + \alpha\, T_r}$$

where t = time in seconds

d = diameter of wire cm.

s = mean value of specific heat of wire in calories per gram per deg. cent. for temperature range

w = density in grams per cu. cm.

I = current in amperes

r_0 = resistivity of wire in ohms per cm.[3]

α = temperature coefficient of wire (average value for temperature range)

T_m = melting point of wire in deg. cent.

T_r = initial temperature.

Such formulas give approximate values, since no account is taken of latent heat radiation, conduction and the effect of wave form, etc. All values are considered as effective values of uniform sine waves of current and voltage.

It is especially difficult to secure accurate values for the power absorbed by the fuse even with modern oscillographic wattmeters because of phase angle, ratio errors, and inductive effects. Unless exceptional care is taken to eliminate such errors, the records of individual trials of watts may vary as much as 1000 per cent. For the same reasons integration of the current and voltage waves is equally unsatisfactory.

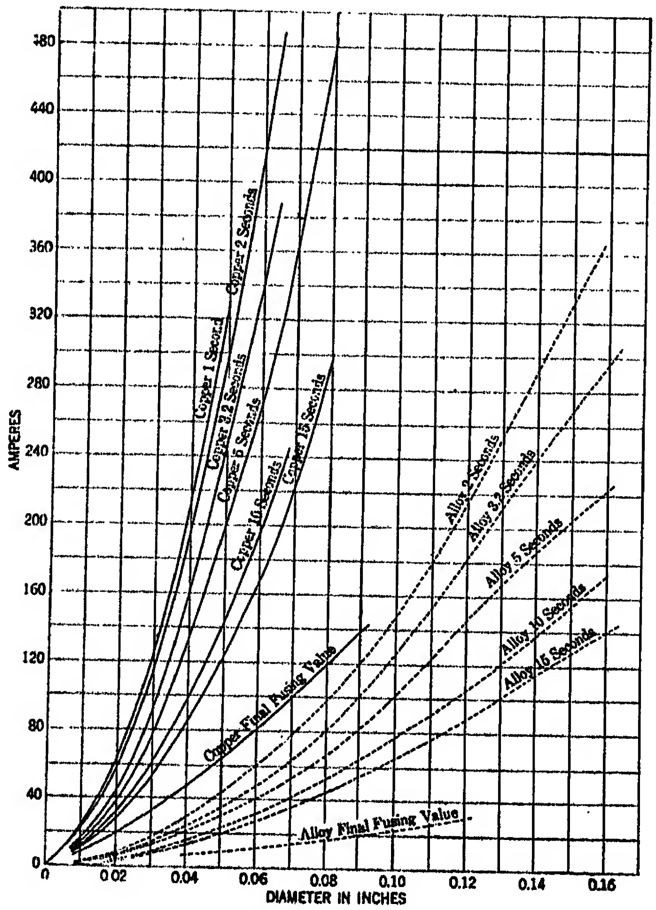

FIG.—1 FUSING CURRENT OF COPPER AND ALLOY FUSES

Comparative data can be secured, however, by averaging a considerable number of trials of each type and the average performance deduced therefrom, as shown in Fig. 1.

In general, if the fuse be tested at low voltage using preferably a good oscillograph and proper control, three or four points plotted on logarithmic paper are sufficient to determine its time-current characteristics. The time clearing characteristics at high voltage, however, do not follow the time fusing curves, since it requires more than the melting of the fuse to clear the circuit, and this time taken up by contact travel or expulsive action is recorded as arc current and is not definitely separated from the true fusing time on the record. The arcing time is moreover dependent upon recovery voltage which is in turn controlled by the connected circuit. The available current is also controlled by the connected circuit and may be many times that required to melt the fuse, frequently volatilizing it directly, whereupon the major portion of the required clearing time is taken up in arcing time.

Since the time of melting is controlled by the size and resistance under control in manufacture, and by the current controlled by the circuit, those fuses having a relatively good conductor of small section such as silver or copper show the most uniform action in service. Silver is particularly desirable since it is not easily corroded under the usual service conditions and the small amount necessary does not form a conducting cloud of vapor such as some of the commoner metals used in low-tension fuses. Nearly all fuses now available have too much metal to be volatilized before they clear, the common expedient of threading a shotgun wad on the element of the expulsion type in order to clear the tube, being a practical demonstration of this fact.

The same limitations which are driving time-current relay settings out of transmission networks in favor of some form of differential or impedance control, operate to limit the success of high-tension fuses for selective clearing of faults. Fuses usually require a far higher current rating on a given installation than the relay setting would be for the same case were it economically possible to use an oil circuit breaker and relays.

The operating requirements of an acceptable fuse may be outlined as follows:

1. Must fuse on a given current in a given time;
2. Must clear circuit under all conditions;
3. Must remain an insulator after clearing.

There might be added desirable requirements calling for the fulfilling of all of the functions of a good relay controlled oil circuit breaker but the above three are fundamental and serve to bar most present day high-tension fuses from being classed as successful when viewed from the user's standpoint.

The present day high-tension fuses may be grouped according to their method of functioning as follows:

1. Plain fusible links
2. Expulsion types
3. Mechanically retracted contacts
4. Explosively propelled contacts.

They all have in common several faults which limit their usefulness. First, the time-current control is very limited; so much so that it is not practical to operate fuses and circuit breakers in series and get selective action where the short-circuit current range is more than two or three to one, because for heavy currents the fuses approach ½-cycle clearing time whereas the relay oil circuit breaker combination have several cycles minimum. The better the fuse as regards its own clearing performance the worse this objection becomes, resulting in a higher rating for a quick acting fuse

for the same duty than for one of the heavier slower acting types.

Practically all fuses now manufactured emit flame and incandescent gas on operation and in addition some types metallic parts and jumpers as well. Few high-tension fuses in commercial use at present are entirely free from this serious objection.

In addition to the above the several types have the following troubles:

Classes one and two above both fail to clear on normal voltage at very slightly above their melting point since the containers, glass, porcelain, or organic material, are all conductors when heated; it follows that if the fuse is gradually heated to incandescence the container will be rendered conducting. Fig. 2 shows examples of such failures. Some rather spectacular results can be expected from either type if the load is gradually increased at normal voltage for several hours and finally allowed to melt the fuse.

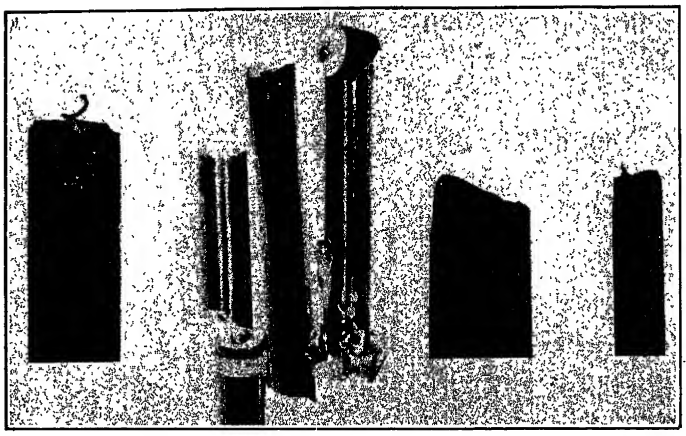

FIG. 2—FUSE CONTAINERS WHICH HAVE BECOME CONDUCTORS BY BEING HEATED

Class three has the primary objection of cost particularly where liquid filled, because of the necessary close supervision in manufacture and careful handling necessary.

They also have to be carefully vented with some form of baffle between the fuse chamber and the liquid in order to prevent shattering the container. In effect this results in an expulsion fuse with a very small chamber and a liquid insulation chamber below.

Under-rating, such as using a 10-ampere fuse in 100-ampere casing, increases the safety but exceeds the economic limit except in very special cases.

In practise considerable care must be exercised in order to prevent liquid leakage either direct or by evaporation.

There are at present very few examples of number four type in service, the so-called shotgun fuse being the best known example. In this type the contact movement is caused by an explosive, usually powder such as is commonly used in fire arms. The fuse itself imbedded in such powder ignites it as soon as either sufficient temperature is reached or an arc is started. The clearing speed is always the same and for this reason the general type is easily adapted to very small fuses at high voltage.

One disadvantage is the necessary clearance required for the exit of flame and contacts.

In application some thought must be given the location of the fuses when blown, a common trouble being to mount them in such a position that when blown in wet weather they will fill with water and thereby become conducting.

AIR BREAK SWITCHES

Because of the lack of available time delay in high-tension fuses and due to the cost of refilling them when blown, many attempts have been made to use automatic air-break switches instead.

The major portion of the air-break switches used for such service are manually closed against a spring or weight and tripped by series overload coils. The tripping is accomplished either direct or through an insulated rod of glass or Bakelite which is used to close a contact on a battery circuit.

The usual clearance between phases is approximately eight feet for 44-kv., and ten feet for 66-kv., and the usual tendency is to carry the arc upward from the insulators rather than across phases.

Practise in automatic air-break switches has demonstrated that the most satisfactory results are secured by moderate speeds, for instance, as the speed usually secured in hand operation from two to four feet per second contact travel.

Compared to high-tension fuses very few automatic air-break switches are in service so that data on their general performance are not readily available.

The same factors which tended in the early days of transmission to force better control of the clearing action and thereby caused development of relays and modern circuit breakers, are operating now to limit the use of the same class of equipment in modern high-voltage distribution lines to those locations where selective clearing action is not essential. For service where overload protection only is desired and moderate interrupting capacity sufficient, present day fuses are reasonably satisfactory.

For higher duties, underrating both in current and voltage minimizes trouble, but is usually not economically feasible.

Motor Control for Wind Tunnel

Precision Speed Regulation for the Wind Tunnel Motor at California Institute of Technology

BY WILLIAM A. LEWIS[1]

Associate, A. I. E. E.

Synopsis.—A wind tunnel for testing model airplanes and their parts requires accurate control of the air velocity. This paper describes a tunnel having electric drive for producing the air movement and explains a system of control, which allows a wide range of speeds and holds the speed very constant at any set value. Either hand or automatic regulation may be employed. The hand control is used for fairly constant speed while the automatic control gives very close regulation.

INTRODUCTION

THE widespread interest in aviation developed during the last few years has resulted in a large increase in the facilities both for teaching aeronautics and for carrying on further investigations in this field. Under the terms of a grant from the Daniel Guggenheim Fund for the Promotion of Aeronautics, a graduate school of aeronautics was recently established at the California Institute of Technology. One of the principal features of the laboratory, built for the purpose of carrying on the experimental work in this department, is a high-speed wind tunnel with a working section ten feet in diameter. The propeller which forces the air through the tunnel is electrically driven, and the equipment and its control present several interesting features, which will be described in this paper.

WIND TUNNELS

Before proceeding to a discussion of the drive, a general description of the tunnel and its use would be desirable. Wind tunnels are used for testing model airfoil sections and new plane designs to determine performance, in the case of planes particularly with regard to taking off and landing. The model to be tested is supported in the center of the working section, usually in an inverted position, and when a stream of air passes the model, the relative motion of air and model simulate flying conditions. The model is supported by wires attached at three points and is held in position by the wires and a series of counterweights. The supporting wires are attached to a set of balances either directly or, as in this case, through a subframe. The reactions of the model may be separated into two components, a force downstream or drag, and an upward force or lift. Since the model is inverted, the upward force with respect to the model is downward with respect to the balances. These forces are instantly felt at the balances and can be computed from the balance readings. The values of the forces together with the temperature, pressure, and velocity of the air, are the data for determining the performance of the model.

This tunnel is of the closed-circuit type, the same air being recirculated. A longitudinal section is shown in Fig. 1. The tunnel occupies a height of nearly four floors, the over-all vertical dimension being about 45 ft. It consists of sections of circular cylinders and cones, connected end-to-end to form the closed circuit shown in the illustration. The four sections in the observation room are made of redwood staves held together by hoops of steel rod and angle iron on the outside. If desired, one or more of the sections may be removed and the tunnel operated with open throat, the circuit being closed by the observation room itself. The remainder of the tunnel is made of reinforced concrete, the interior surface of which was formed by the Gunnite spraying process. At the intersections of the vertical and horizontal sections a series of deflecting vanes changes the direction of the wind with minimum loss of energy. The completed vane installation in the lower 20-ft. intersection is shown in Fig. 2. The vanes in the two left-hand corners are arranged so that at a future date, cooling water may be circulated through them to assist in cooling the air in the tunnel. The entire tunnel is supported on its own foundation free from the building, to minimize transmission of vibration.

WIND VELOCITY REQUIREMENTS

For preliminary work it is desirable to control the velocity of the wind from the observation room, but for accurate testing the performance is determined entirely from the balance readings so that the balance operator must have instant and accurate control over the propeller speed. Because of the many variables involved, engineering accuracy requires that the variation in each, particularly wind speed, be kept as small as possible. The maximum allowable variation in propeller speed for satisfactory operation is $\pm$ 0.25 per cent. At the same time, in order to make a complete series of tests it is necessary that the air speed be adjustable over a wide range.

To fulfill these requirements the equipment described below was designed and installed. With it,

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any wind velocity past the model from a slight breeze produced by a propeller speed of only about 40 rev. per min. to a cyclone of approximately 200 mi. per hr. at a propeller speed of 850 rev. per min., can be easily obtained by operating a single control, located at any point desired. Within the range from 130 to 850 rev. per min. the speed control can be transferred to a regulator which will maintain the speed constant with a

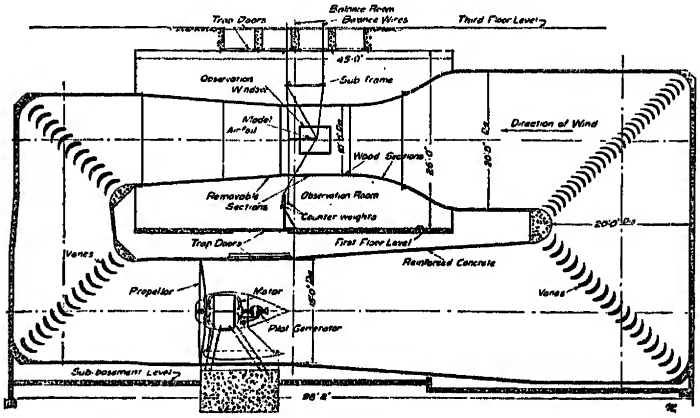

FIG. 1—LONGITUDINAL SECTION OF THE WIND TUNNEL (VERTICAL PLANE)

very high degree of accuracy. This range corresponds to air velocities of 10 to 200 mi. per hr. By adjusting the positions of a coarse and fine rheostat, one of which is located at each station, the speed held by the regulator may be easily adjusted to any value in its range.

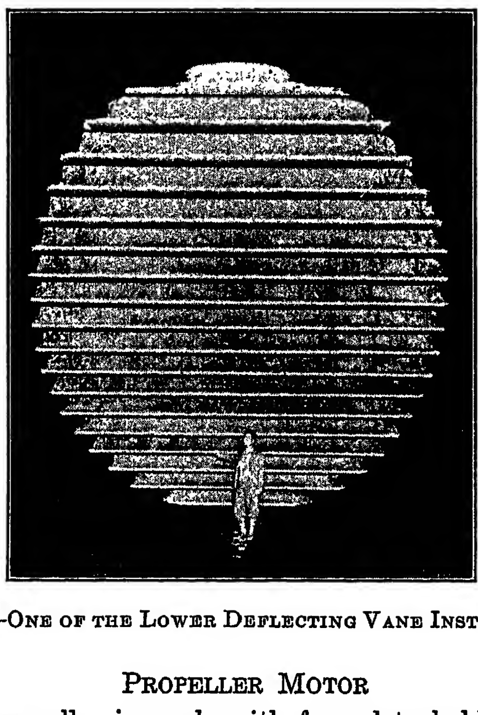

FIG. 2—ONE OF THE LOWER DEFLECTING VANE INSTALLATIONS

PROPELLER MOTOR

The propeller is made with four detachable blades mounted in a central cast hub. The diameter of the propeller is 14 ft. 11 in. and of the tunnel at the section where the propeller is located approximately 15 ft., so that clearance between the propeller and the tunnel wall is very small. After consideration of all advantages and disadvantages, it was decided to place the motor inside the tunnel, supporting it on a structural steel frame extending out through the walls of the tunnel into a heavy concrete base, and to mount the propeller directly on the end of the motor shaft. The obstruction introduced is not serious if the motor and its framework are not too large, since aerodynamical considerations require that the wind stream be contracted just beyond the propeller.

To drive the propeller at the maximum speed requires an input of approximately 750 hp. However, the time for obtaining a set of readings is not great and it was estimated that a machine of 500 hp. continuous capacity with short-time overload ratings, would be satisfactory. The standard machine of this size is equipped with bed-plate and pedestal bearings, and was not well adapted for the type of mounting required. A special

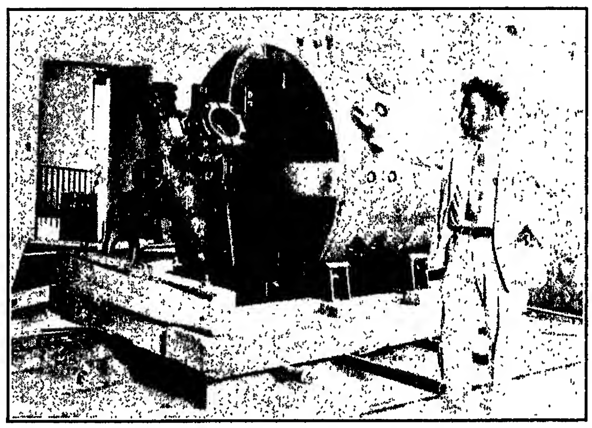

FIG. 3—PROPELLER MOTOR, 500 HP. CONTINUOUS RATING

design, with bearings mounted in end brackets supported directly from the motor frame, developed for submarine and other transportation purposes, solved the problem. In this way a motor having a completely cylindrical frame and an over-all diameter of only 4 ft. 8 in. was obtained. The motor, before installation, is shown in Fig. 3. The feet shown in the figure were used for transportation only, it being found that a smaller over-all diameter of motor and covering would result if the feet were eliminated, and the supporting framework made to fit the motor frame. Because of the errors which would be introduced into the speed regulation by vibration, the framework was made very heavy and rigid so that its natural frequency is far higher than any introduced by the propeller. A semi-cylindrical steel-plate cradle fits the lower half of the motor frame and is bolted directly to the motor. Four heavy H-section columns form the supporting legs and are riveted to the cradle. In assembling, the heavily reinforced concrete base for the framework was first cast complete, with the exception of four pockets for the legs. The legs were then inserted in these pockets, and

the cradle riveted to the legs. Next the motor was mounted, the entire structure alined as a unit, and the pockets filled with concrete to unite the framework and base into a continuous whole. The U-shaped pockets in the rear H-section legs were covered with steel plates and used for wiring gutters, cored ducts in the concrete base forming a continuation of these gutters to accessible locations. The details of the structure can be seen in Figs. 4 and 5.

Cooling the Motor

One serious problem, introduced by mounting the motor inside the tunnel, is that of securing adequate

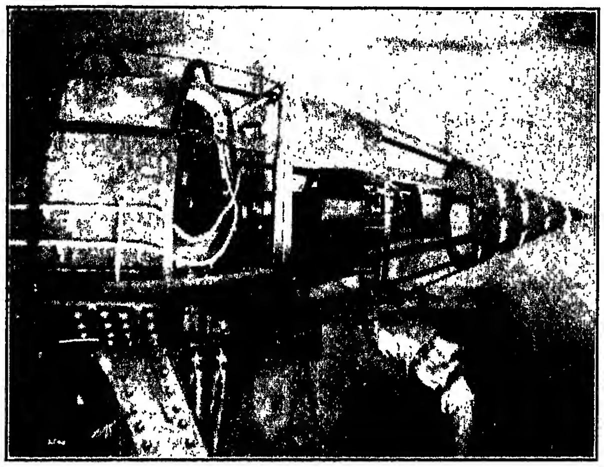

Fig. 4—Propeller Motor and Pilot Generator Mounted in the Tunnel and Partly Covered by Stream Line Fairing

ventilation and cooling. The entire output of the propeller is eventually converted into heat by friction of the air, and since the air is recirculated, this heat, together with that due to the losses in the motor, will be taken up by the air and walls of the tunnel. As data for determining the heat transfer from the air to the tunnel walls were meager and inaccurate, it was impossible to predict the temperature to which the air would rise or the time required to reach equilibrium. If the tunnel air remained within reasonable temperature limits, it could be used for cooling the motor, but an air temperature much in excess of 50 deg. cent. would make a separate cooling system necessary. Several estimates placed the average air temperature in the tunnel at 45 deg. cent. Because of the expense of external cooling and in view of the difficulty of carrying on work in the observation room when the temperature of the tunnel is excessive, it was felt that use of the tunnel air for motor cooling would be satisfactory. Part of the air from the propeller is deflected through the motor air passages.

In order to keep the friction loss caused by the air passing outside the motor at a minimum, it was necessary to enclose the motor and its support in a stream line fairing, broad nosed at the propeller end and tapering off to a point at the tail. An opening in the nose and louvres in the sides allow the ventilating air to pass through the motor. In order to keep the pilot generator, (a small generator connected to the main shaft and used with the speed regulator) at as constant a temperature as possible, it is ventilated separately. A baffle inserted between the two machines produces the desired result. A second set of louvres behind the baffle and a third set in the tail provide the necessary cooling air circulation. The fairing is composed of a skeleton framework, Fig. 4, covered with steel plates screwed in place. The section covering the propeller hub revolves with the propeller but the remainder is stationary. To obtain access to any part of the motor it is necessary merely to remove the adjacent plates. An ingenious assembly of the skeleton frame allows a large section of the fairing to be removed as a unit in case of major repairs. Views of the fairing framework with several of the plates mounted are shown in Figs. 4 and 5. After the fairing of the motor itself had been completed, the legs on each side of the shaft were enclosed in additional fairings. Views of the completed installation are shown in Figs. 6 and 7.

Motor-Generator Set

The propeller motor is a d-c. commutating pole machine, since such a speed range could not be obtained with constant frequency alternating current. For furnishing the direct current and providing a simple means of speed variation, an individual synchronous

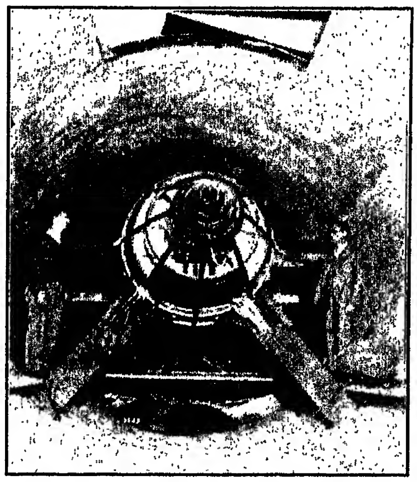

Fig. 5—End View of Motor Showing Supporting Legs Used for Wire Gutters

motor-generator set is provided. In order to make available the maximum possible amount of direct current for physical experiments, the nominal d-c. voltage was established at 230 volts, although the actual voltage varies from residual of the generator up to about 300 volts, depending upon the speed of the propeller motor. Both the synchronous motor and the d-c. generator are provided with direct-connected exciters, separate machines being required because of the speed regulator.

Method of Control

As the motor-generator set had to be located quite

close to the propeller motor, because of the large currents involved, it was placed in the sub-basement of the building, just outside the tunnel. The most desirable location for the control station being near the balances in the balance room, five floors above, electrical remote control was adopted for all equipment requiring operation during normal running of the tunnel.

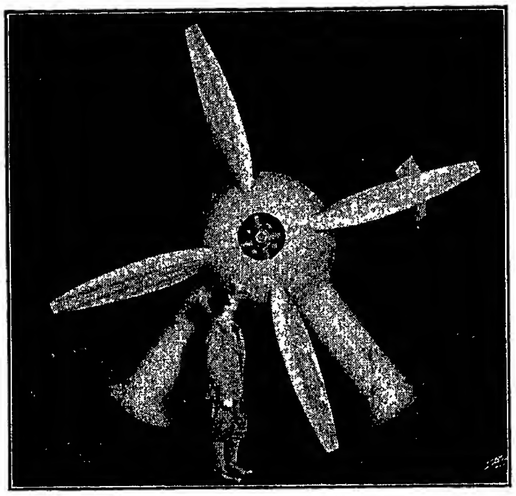

Fig. 6—Propeller End of Main Motor with Fairing Completed

Direct current was considered the most suitable for control power, and continuity of service not being absolutely essential, a small induction motor-generator set, giving 125 volts direct current was provided instead of the more expensive storage battery. The former type of control, however, is not absolutely reliable and provision had to be made for disconnecting all the main machines upon failure of control voltage, thus complicating the control circuits considerably.

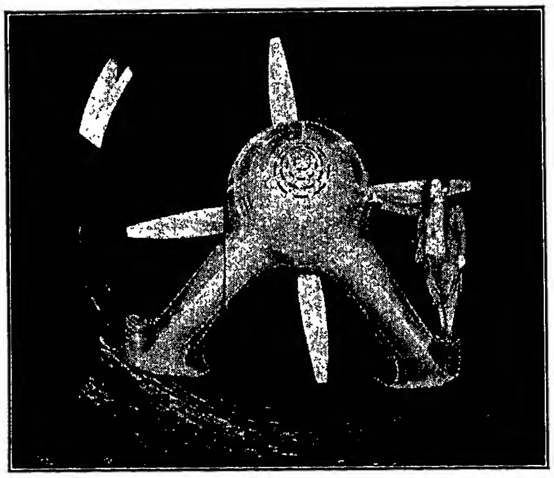

Fig. 7—Down Stream End of Main Motor Showing Completed Installation

The apparatus for starting and controlling the a-c. end of the motor-generator set is practically standard automatic equipment and need not be described here. However, since the propeller motor is neither visible nor audible from the point of normal operation and the operators are in general non-electrical men, it was considered worth while to design the entire installation for unattended operation and most of the features common to automatic stations, such as lock-out relay-bearing temperature relays, reverse-phase voltage, current relays, etc., are provided. Also the switching operations of starting are automatically controlled so that the field is applied and the transfer to full voltage is accomplished without the intervention of the operator.

To secure the wide speed range necessary for the propeller motor, the armature voltage or Ward Leonard system of control is necessary. To obtain good efficiency and regulation with this system it is necessary to vary the voltage of the generator which supplies the motor armature. Control is exercised in this case by

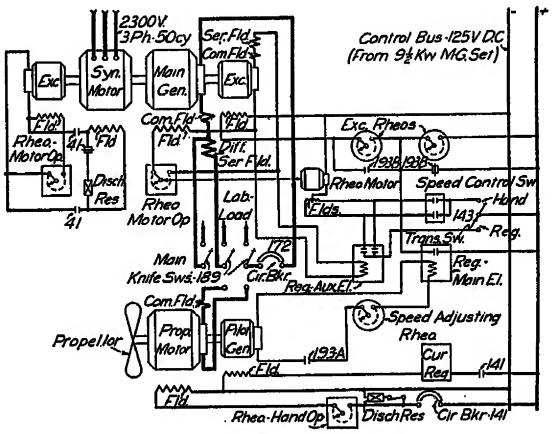

Fig. 8—Schematic D-c. Circuits for Automatic Speed Control and Power Supply

varying the excitation of the generator either by changing the position of the generator field rheostat or the voltage of the exciter or both. The field of the motor must, of course, be supplied from a separate constant-voltage source and in this case was connected to the control generator because the voltages of both direct-connected exciters for the motor-generator set are subject to excessive changes. This connection also resulted in the smallest installed auxiliary capacity, since field for the propeller motor is not required until all the large oil circuit breakers have been closed and the closing solenoids deenergized, thus making possible joint use of the same control-generator capacity. The main d-c. connections are shown in Fig. 8, and the armature and field circuits may be easily traced on the diagram. It will be noticed that a series of double-throw switches is inserted in the armature circuit of the main generator and that the two right-hand switches must be closed in the lower position in order to connect the propeller motor. Under these conditions the differential series field is in circuit, acting to stabilize the speed by opposing a change in current. When the

generator is used for other experiments, the differential field may or may not be desired and the third switch allows a choice to be made.

It may also be noticed that no starting resistance is provided in the propeller-motor circuit. The starting current is kept within sufficiently low limits by reducing the generator voltage to its minimum value before closing circuit breaker 172. It is also necessary, of course, that the field circuit be closed before the armature circuit is closed, and that the armature circuit open whenever the field circuit opens. These conditions are obtained by means of suitable interlocks so that circuit breaker 172 cannot be closed until the motor-operated rheostat is "all in," and as soon as the circuit breaker opens, connections not shown in the diagram run the rheostat to this position. The motor is started by operating a single control switch. If the rheostat is in the proper position, the motor starts immediately. If not, the motor will start as soon as the rheostat reaches the "all in" position. The connections are arranged so that field circuit breaker 141 closes first, followed by the closing of circuit breaker 172. When stopping, whether by hand or by one of the protective features, the breakers open in the reverse order. If the field breaker opens for any reason, the armature circuit breaker opens immediately.

After the motor has been started, two types of speed control are available. Under hand control the speed of the motor is brought to the desired value and remains nearly constant due to the inherent regulation of the system, although small variations and a gradual creep in speed, due to temperature effects, occur. However, this type of control is much simpler and is very satisfactory for rough or preliminary work. Under regulated control the speed is set at a given value corresponding to the position of the speed adjusting rheostat, consisting of a coarse and fine section, separately adjustable, and is held at that speed with a high precision by the speed regulator. Although several control stations of both types are provided, only one of each is shown in the diagram. To accommodate additional stations the number of positions of transfer switch 143 is increased, and additional speed adjusting rheostats and relays, 193, are provided for each regulated station and additional speed control switches for each hand control station. For hand control, the entire adjustment is obtained by control of the generator field rheostat, whereas the two elements of the regulator control both the voltage of the exciter and the position of the generator rheostat.

For hand control, transfer switch 143 is closed in the hand position, thus connecting the speed-control switch to a source of power, and the operation of this switch will cause the rheostat to be driven in one direction or the other, thus increasing or decreasing the generator voltage and consequently the speed of the propeller motor. It may be noticed that there are two rheostats in the exciter field circuit, so that the voltage of the exciter is dependent on the position of both rheostats. However, under hand control, relay 193-B is deenergized so that its back contact is closed, short-circuiting the right-hand rheostat, and the exciter voltage is thus determined in this case entirely by the position of the left-hand rheostat. The latter is set at a position which will give normal exciter voltage and is left unchanged, so that the generator rheostat has complete control of the propeller-motor speed.

To obtain regulated control, transfer switch 143 is changed to the "Reg." position. Auxiliary circuits, not shown, immediately run the generator rheostat to the "all in" position, and energize relays 193-B and 193-A. Relay 193-A connects the pilot generator armature to the main element of the speed regulator through the speed adjusting rheostat. Relay 193-B short circuits the left-hand exciter rheostat and inserts the right-hand one in the circuit. The field of the pilot generator is energized through an auxiliary contact of the field circuit breaker 141 and the current regulator, and therefore carries a constant current whenever the propeller motor is running. Under these conditions the voltage generated by the pilot generator is directly proportional to speed. A definite fraction of this voltage, depending upon the position of the speed adjusting rheostat, is impressed upon the main element of the regulator. If this voltage is below the amount required to open the regulator contacts, the contacts close and short-circuit the exciter rheostat. This raises the exciter voltage, hence also the generator voltage, the motor speed, and the pilot generator voltage. If the increase in pilot generator voltage is sufficient, the contacts will open, the exciter voltage will fall and with it, the generator voltage, the propeller motor speed, and the pilot generator voltage, until the contacts close again. The process repeats continuously. An auxiliary coil and plunger, not shown in the diagram but connected across the exciter terminals, react on the contacts in the same manner as the d-c. coil in an a-c. generator voltage regulator, preventing hunting and keeping the oscillations in speed, produced by the above described opening and closing of contacts, within the most minute limits. Under this condition the mean speed is a function of the position of the speed adjusting rheostat, since the average current in the regulator coil must be a constant and the drop across the rheostat then depends only on its position.

If, in the first instance, the increase in pilot generator voltage was insufficient to open the contacts, the vibrating action does not occur and a speed balance is not obtained. The speed range over which a balance can be obtained with a fixed position of the generator field rheostat is very small, and to increase this range, the auxiliary element of the regulator is provided. If the main contacts remain closed, the exciter voltage will rise above a predetermined value at which one of the contacts of the auxiliary element closes, and this contact changes the position of the generator rheostat until the

regulator contacts open, the exciter voltage falls, and the auxiliary contact opens again. Conditions are now satisfactory and the vibrating action of the contacts is immediately set up and a balance obtained. In case the resistance in the speed-adjusting rheostat is reduced, the regulator contacts immediately open, reducing the exciter voltage, the generator voltage, the motor speed, and the pilot generator voltage in turn. If the drop is sufficient, the contacts will close again, a new vibrating action will be set up and a new speed maintained. If the contacts do not close, the exciter voltage will fall so low that the other contact of the auxiliary element will close, increase the resistance in the generator field, reduce the speed of the propeller and finally the pilot generator voltage, until the contacts again close and a new vibrating point is established. Thus, the quick-acting vibrating regulator maintains a precision control over a narrow range and this range is shifted to the proper part of a much broader range by means of the auxiliary element, thus providing a precise speed control over a broad range.

Operating Results

The installation described above is giving entire satisfaction in the operation of the wind tunnel at California Institute of Technology, both with regard to ease of control and accuracy of speed regulation. Although no precision instruments are available for measuring the actual instantaneous variations, observations of an accurate electric tachometer indicate instantaneous variations of less than 0.2 per cent plus or minus, after the regulating equipment has assumed operating temperature, requiring about one half-hour.

There are innumerable causes of instantaneous speed variation, the principal ones being resistance changes due to temperature variations in the armature and field of the propeller motor, main generator and exciters, change in load due to change in angle of attack of the model, change of supply frequency, etc. However, none of these changes can exceed the limit given above of ± 0.2 per cent without bringing about a corrective action from the regulator, so that none of these effects produce any permanent variations or any beyond the stated limits unless they are of such extreme magnitude and so rapid that the regulator is unable to respond and correct them before the limit is reached.

The only causes of permanent variation are those which affect the accuracy of the speed regulator, and include changes in resistance of the regulator circuits and change in permeability of the pilot-generator field with temperature. Such effects cause a gradual increase in speed of approximately 0.25 per cent per hour after operating temperature has been reached, and may be easily corrected for by adjustment of the speed-adjusting rheostat.

As explained above, no permanent speed change is caused by variation in a-c. line voltage or frequency, the changes being immediately corrected for by action of the speed regulator. No data are available regarding the speed of corrective action of the regulator or the amount and rate of change necessary to prevent the regulator keeping the speed within the allowable limits. Although the assembly was developed for a special application, it is composed entirely of standard apparatus and has several features which may be adaptable to other purposes requiring a wide speed range with a high degree of accuracy in speed regulation.

Acknowledgment

The author wishes to acknowledge the kind cooperation of many members of the staff of the California Institute of Technology, especially Mr. L. G. Fenner, Superintendent of Wiring; also of many members of the engineering staffs of the Westinghouse Electric & Manufacturing Company and General Electric Company.

Appendix

Apparatus

Propeller Motor: 500-hp., 230-volt, 700-rev. per min., at full load, shunt connected.

Main Generator: 430-kw., 230-volt, 1000-rev. per min., differential compound.

Main A-C. Motor: 610-hp., 2200-volt, 3-phase synchronous.

M-G Set for Control Supply: 9½-kw., 125 volt, 1500-rev. per min. compound generator; 220-volt, 3-phase induction motor.

Pilot Generator on the Propeller Motor Shaft: Rated 1.5 kw. (but in a larger frame for negligible temperature rise) 600-volt, 700-rev. per min., separately excited.

Automatic Switchboard contains: 3000-ampere automatic circuit breaker, accelerating relays, misc. relays, field contactor, overload relays, annunciator relay.

Speed Control Switchboard contains: Phase balance relay, voltage balance relay, control switches and indicators and regulator operating from the pilot generator.

Much additional apparatus such as exciters and switchboard meters have not been listed in detail.

The Electrical Engineering of Sound Picture Systems

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Synopsis.—*The paper describes the technique and apparatus of sound picture recording and reproduction, with emphasis on their electrical engineering aspects.*

The various steps in the processes of disk and film recording are outlined as they take place in the Western Electric systems. Microphone placements, sound insulation, monitoring and mixing, and the circuits for amplifying currents and distributing them to recording machines are discussed. This is followed by a description of the disk and film recording machines.

The changes which have been required in theater equipment to provide for the reproduction and projection of sound in synchronism with motion pictures are outlined.

Some of the laboratory developments and studies out of which recording and reproduction methods have grown are given brief mention.

THE sound motion picture, youngest of the arts, is a development of electrical, mechanical, and chemical science. The electrical development in the motion picture industry was at first a normal one which kept pace with the demands of the industry with respect to light and power. Then came an event which was sudden and dramatic. The motion picture industry was, literally and figuratively speaking, electrified. It was realized that laboratory research work directed toward improvement of the telephone and the radio could be combined with the motion picture and the silent screen given a voice. The sound picture is a combination of the silent motion picture and the electrical pick-up, amplification, transmission, recording, and reproduction of sound. The essentials of the sound processes are the recording and synchronizing of sound on either film or disk records with a satisfactory method of synchronized reproduction.

At first sound pictures were a novelty. People attended the theaters out of curiosity. Motion picture actors were vitally interested in voice tests. Many mishaps and troubles occurred as well as amusing incidents regarding the use of the strange recording equipment. Finally, sound recording methods have been adapted to motion picture production requirements and the motion picture industry has started the serious production of sound pictures for entertainment with success a certainty.

That the development of sound recording and reproduction should be closely related to that of the telephone is only natural since many of the fundamental principles are similar. In what follows the authors will have in mind principally the Western Electric systems of recording and reproduction.

Sound picture production requires the *faithful recording of sound in synchronism with a motion picture,* and the *faithful reproduction of the sound in synchronism with the projected picture,* in order to create the illusion that the actor in the picture is actually talking or singing.

Sound Picture Recording

The electrical recording of sound requires a method of transforming sound vibrations into electric currents, then the transmission, control, and amplification of these currents, and finally a method of changing the electrical energy into mechanical energy in order that a permanent record may be had on the recording medium either by modulated light on a sensitized film or the movement of a cutting stylus in soft wax. What the purely electrical operations involved chiefly do is to assist in the pick-up of different sound sources, the transmission of these vibrations, and their amplification (or reinforcement) in any desired amount.

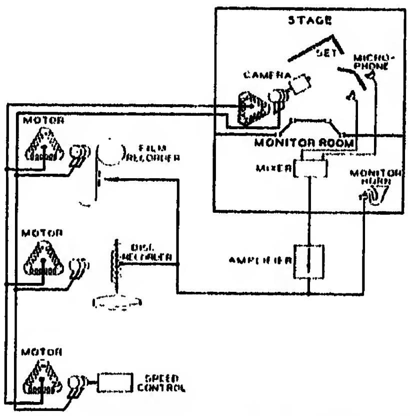

Fig. 1—Schematic Diagram of Recording System

A schematic drawing of a studio recording system in simplest form is shown in Fig. 1. The essential parts of such a system consist of microphone pick-ups on the stage, a mixer and volume control in the monitor room, system and monitor amplifiers, recording machines, and a synchronous motor system for synchronizing the recorders with the cameras. These various component parts of the system will be explained in more detail.

The recording stages (called sound stages) are constructed in such a manner that external noises may be excluded. The reason for this is, of course, obvious. Usually soundproofing is accomplished by the use of double or triple walls with intervening air spaces for deadening. The interior treatment of the sound stage is also of interest. The walls and ceiling are usually covered with sound absorbing materials. The choice of a particular material depends upon the amount of sound absorption needed, and upon the frequency absorption characteristics of that material, since all materials do not absorb the various frequencies uniformly. If a

1. Electrical Research Products, Inc.
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large amount of material of high absorbing ability is used, the stages become "dead," which means that very little reflection of sound from surfaces takes place. If too little or too inefficient absorbing material is used, the stage is objectionably "live." A condition between these extremes must be generally sought. Portable damping in the form of large flats covered with acoustic material is also used. A cross section of a typical wall construction is shown in Fig. 2.

The monitoring rooms are sound treated somewhat in the same way as are the sound stages. This is done

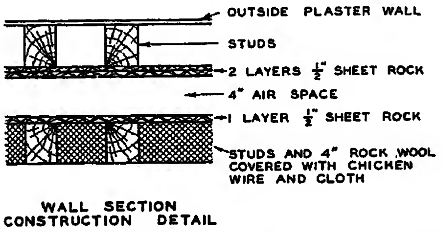

FIG. 2—CROSS SECTION OF TYPICAL SOUND STAGE WALL CONSTRUCTION

in order to exclude all sounds except those which the monitor man wishes to hear, and to provide the proper acoustical conditions.

During the recording of a scene, there are many problems that confront the monitor man. The microphone or microphones must be placed in such positions as to pick up satisfactorily the speech or music occurring on the set. Often the location of the microphone is complicated by the construction of the set, and by the necessity for keeping it out of the field of view of the camera. The microphone may be mounted on a floor stand, hung

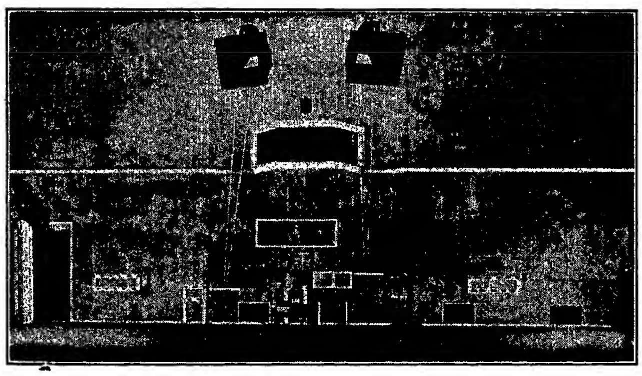

FIG. 3—INTERIOR OF SOUND STAGE

Note monitor window and horn used by monitor man when talking to people on stage

from the ceiling, or as is more often the case, suspended from the end of a long boom which has numerous adjustments for vertical and horizontal motion. The type of microphone used is the condenser transmitter. Fig. 4 shows a view of this instrument, with its associated amplifier. It is essentially a condenser, in which one of the plates is a very thin stretched sheet of duralumin, which may be set in vibration by sound waves. Thereby the capacity of the microphone is varied and an electromotive force set up in the electrical circuit to which the microphone is connected. If the microphone is made to have its diaphram resonance above the range of frequencies being recorded, it will transmit this range with very little distortion. Fig. 5 shows a typical frequency response characteristic of a microphone of the condenser transmitter type.

Various kinds of materials are used in the con-

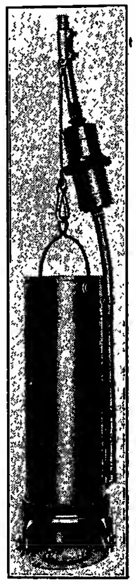

FIG. 4—CONDENSER TRANSMITTER MICROPHONE WITH ASSOCIATED AMPLIFIER

struction of sets, although the general tendency is to use those materials which are sound absorbing. The sets may have two or three walls, very seldom being completely closed. These varying conditions make it necessary for the monitor man to locate his pick-ups carefully in order to achieve the best results. Some monitor men prefer to use only one microphone while others are accustomed to use a number of microphones.

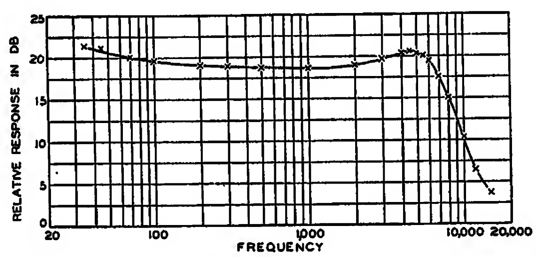

FIG. 5—FREQUENCY RESPONSE CHARACTERISTIC OF CONDENSER TRANSMITTER MICROPHONE

All these factors, together with the personal element introduced by the actors themselves, constitute a difficult and important problem for those who operate sound equipment.

During actual recording, the director, as well as all other onlookers, must remain absolutely quiet. Rustling movements, footsteps, or a cough, are readily recorded.

In order to eliminate camera and motor noise camera booths have been used which are constructed of sound proof material with a clear glass window in front for the camera to "shoot" through. The booths are usually

FIG. 6—VIEW OF STAGE AND SETS FROM MONITOR PLATFORM

constructed in two sizes, accommodating one or two cameras. When two cameras are used, one, by means of a special lens, provides the "close up," the other camera being used for the "long shot." The camera

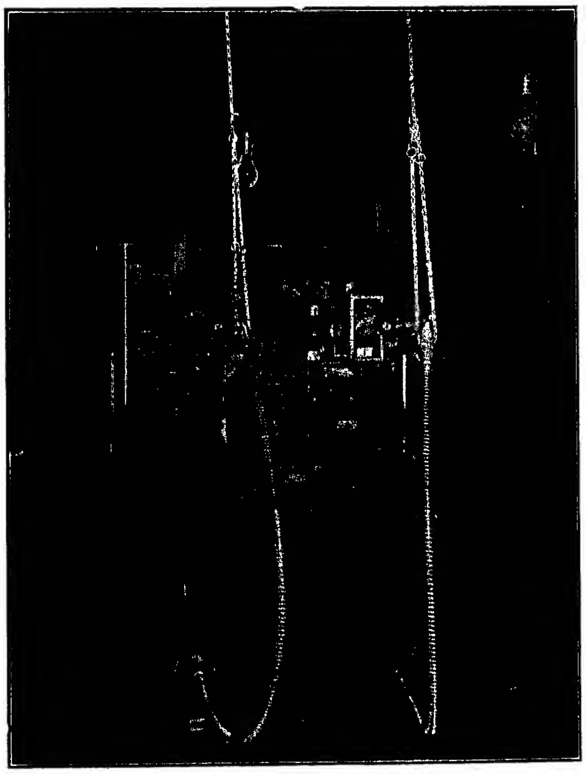

FIG. 7—INTERIOR OF CAMERA BOOTH
Note motors and flexible drives to cameras. Prologue set of "The Iron Mask" may be seen through the glass window

booths are mounted on rollers so that they may be moved about, but at best they have proved a clumsy and awkward expedient. The development of silent cameras and drives is now under way so that camera men may employ methods similar to those used in photographing silent motion pictures. The new sound devices have placed many rigid technical obstacles in the path of motion picture production, but gradually these various obstacles are being eliminated so that the freedom of silent motion picture days may again be realized. Several camera booths are used in photographing a scene. In this way various angles may be photographed simultaneously in synchronism with one sound track. The film cutter is then free to use any camera angle or close up that will enhance the dramatic and artistic effect of the finished picture.

The monitor man is responsible for the balance, quality, and volume of the recording. It is his duty to be thoroughly familiar with the action being photographed, the acoustic conditions of the set, and to properly locate the microphones for the best over-all results. He sits at a bay window in the monitor room with a clear view of the stage. (Fig. 8.) Sounds are heard from the stage by means of electrical pick-up and monitor horns

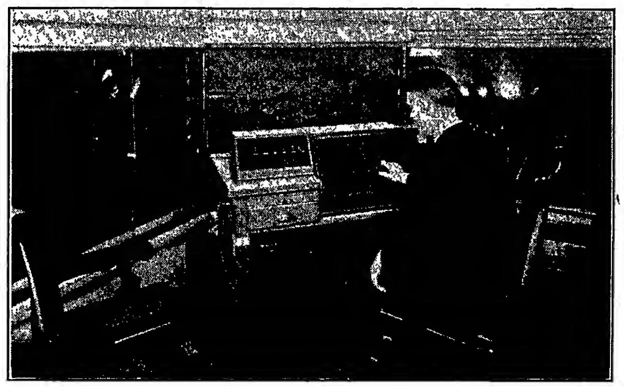

FIG. 8—THE MONITORING BAY AND CONTROLS

only, since the monitor room is insulated from the stage by sound-proof walls. The monitor room simulates theater reverberation conditions, thus assisting the monitor man in obtaining the best recording results from the theater patrons' "auditory viewpoint."

The mixer table is the centralized control of the system. Controls are located here for fading in and out microphones, maintaining the volume balance between several microphones, and regulating over-all volume; also for operating communication systems, signal lights, and relay control switches. The volume indicator provides a visual method for the monitor man to keep the sound volume range within the limits of the recording system.

Fig. 9 shows a more detailed schematic of the amplifier and recording systems. The microphone junction box which permits the interconnection of different microphones, is located on the stage. Flexible cables from the microphones are connected to this box. The microphone circuits enter the mixer on the control platform where the mixing operation is performed and amplification obtained before trunking to the recording building. In the recording building, which is usually separated from the stages because of the fire

hazard, is concentrated all the recording, power, and auxiliary equipment except that mentioned above. In this building are located the wax shaving room (for preparing wax records), battery room, motor-generator room, "dubbing"[3] room, film loading room, recording rooms, test laboratory, and amplifier room. (Fig. 10.)

The amplifier room contains the system amplifiers, monitor amplifiers, and power control panels for all the channels. "Channel" is the designation for all the equipment associated with one stage.

Bridging amplifiers with impedance relations and circuit arrangement such that little or no loss or distortion is introduced into the circuit, divide the electrical circuit four ways. The bridging amplifier outputs are connected to the wax and film recording machines in the recording room. The electrical wax recorder requires approximately +8 to + 10 db. volume level, the light valve on the film recorder about +0 db.[4] (Fig. 11.)

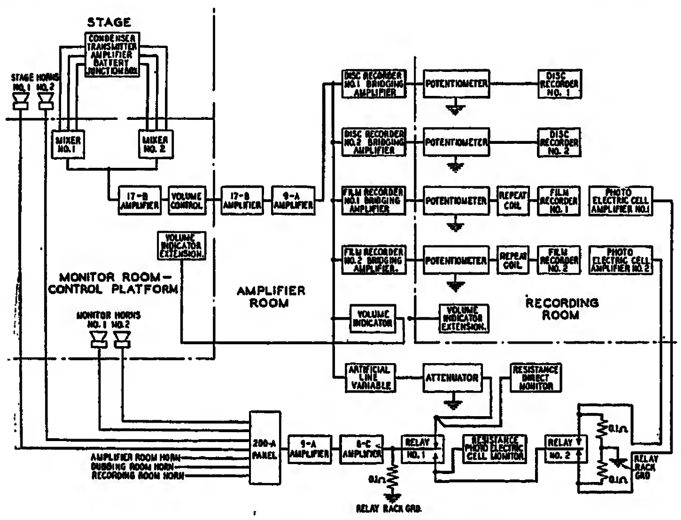

FIG. 9—SCHEMATIC DIAGRAM OF ONE COMPLETE RECORDING CHANNEL

The volume level for each recording machine may be adjusted by variable attenuators adjacent to the machines. If the picture is to be released with the sound recorded on film, it is common practise to operate two film recording machines for the permanent film record and one wax recorder for playback purposes.

Monitoring is accomplished in two ways,—direct and indirect. The direct monitor circuit originates at the bridging bus and by means of an artificial line, attenuator, relay, and amplifier system is connected to the horns in the monitor room. This affords a very accurate method of determining the balance, volume, and quality of the stage pick-up and is useful in predetermining during rehearsal the location and number of microphones necessary for a particular scene. The indirect monitor provides an opportunity to judge the quality of the recording at the point where the sensitized film is actually exposed. Possible overloads of the light valve and noise or distortion are easily detected. This method of monitoring insures favorable recording conditions, or the immediate detection of trouble.

In the film recorder a photoelectric cell is located in back of the film and in line with the modulated light

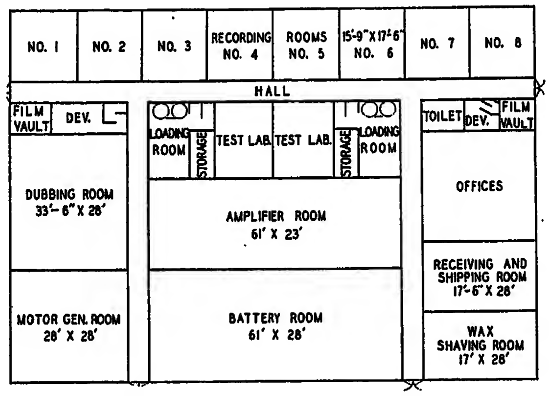

FIG. 10—RECORDING BUILDING FLOOR PLAN

beam striking the film from the front. A small amount of modulated light is transmitted through the film and reaches this photoelectric cell which transforms the light into a weak electric current. This current is amplified by a photoelectric cell amplifier attached to the recorder. The output is connected to the monitoring circuit in the amplifier room where sufficient amplification is obtained to provide loud speaker volume. By

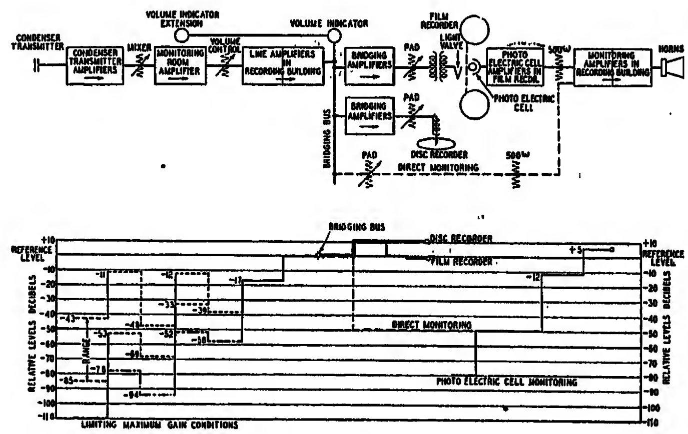

FIG. 11—SCHEMATIC CIRCUIT OF RECORDING CHANNEL AND VOLUME LEVEL DIAGRAM

means of relays controlled from the monitor platform, the monitoring horns may be connected to either direct or indirect monitor during the recording process, and by the use of an artificial line the volumes of the direct and indirect monitor are balanced.

The recording rooms usually contain two film recording and two disk recording machines. These machines are associated with one recording channel. They are

3. "Dubbing" signifies a copying or combining process effected through re-recording.

4. The zero reference level is an arbitrary reference level which is determined by the output of a particular type of vacuum tube. *Each* 10 db. above or below this level signifies a multiplication of the power *tenfold* or a diminution to *one-tenth.*

all driven by synchronous motors in synchronism with the camera motors on the stage.

The wax recording machine, used in the Western Electric system of disk recording, may be compared to a high-grade lathe. (Fig. 13.) The machine consists of the following parts: a motor drive, a reduction gear

FIG. 12—AMPLIFIER ROOM—POWER CONTROL PANEL AND AMPLIFIER EQUIPMENT FOR EIGHT CHANNELS

with a belt drive connected to the lead screw, which moves a recorder radially across the surface of the wax disk, and a second reduction gear driving a turn-table on which the wax is placed. The second reduction gear reduces the motor speed of 1200 rev. per min. to a turn-table speed of 33⅓ rev. per min. A damping arrange-

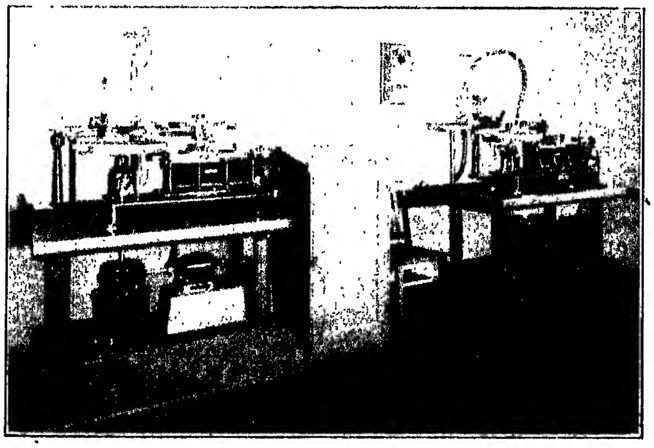

FIG. 13—WAX RECORDING MACHINES

ment, consisting of two sets of vanes placed in oil, damps natural periods of oscillation.

After the disk has been polished it is placed on the turn-table of the recording machine. The recording is made with an electrical recorder which receives its power from the system amplifiers. The electrical energy drives a recording stylus. The recording stylus, made of sapphire or ruby, must be sharp and of a shape to insure a clean cut, since any roughness in the walls of the groove introduces extraneous noise in the reproduced sound. The records used in the Western Electric system are lateral cut records, in which the grooves are of constant depth and oscillate about a smooth spiral. To maintain the cut at the correct depth, a so-called advance ball is used which rides lightly on the polished surface of the disk and supports the stylus. A microscope is employed to observe the groove during this adjustment and during the recording process. The recorders have been designed to operate over a range of frequencies from 30 to 6500 cycles per second.

After a record has been cut, two procedures may be followed,—the record may be processed for use in theaters, or the sound may be reproduced directly from the wax records by means of a "playback" reproducer. The "playback" reproducer does not rest on the record as those used in theater or phonograph reproduction, but is supported by the carriage and driven by the lead screw of the recording machine. The vertical pressure

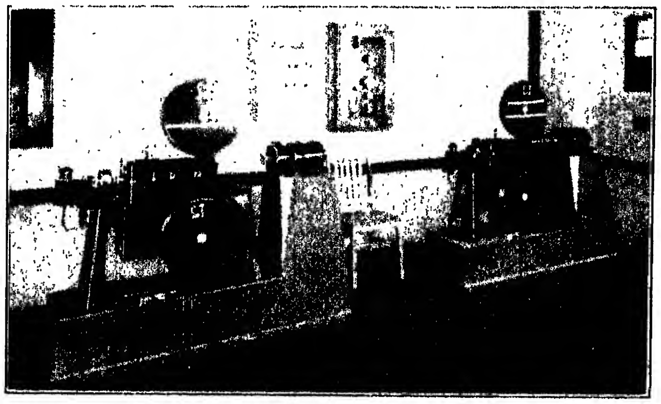

FIG. 14—FILM RECORDING MACHINES

of the needle point on the record has been reduced to a minimum. Since the groove has to drive the needle point of the reproducer properly, reduction of the vertical pressure means reduction of the mechanical impedance offered by the needle point to transverse vibration. To accomplish this, the mass and stiffness of the playback reproducer have been determined so that the response of the playbacks in use at present compares favorably with that obtained from finished records. The use of the wax playback has proved advantageous to the director and actors in immediately judging the dramatic effect and the quality of a recorded scene without the necessity of waiting for the film or wax record to be processed.

The film recorder (Fig. 14) and its driving motors are usually mounted on the same base which in permanent installations is a concrete slab insulated from the building structure by means of cork mats to prevent the transmission of excessive vibrations to the recording machine.

The machine contains a mechanical damped film

drive mechanism, and by means of a lamp, lens assembly, and light valve, records sound on the film.

Referring to Fig. 14, the film recorder control and power panel may be noted on the wall. Adjacent to the panel is a dessicator for storing light valves.

The light valve[5] is an electromechanical shutter actuated by amplified sound currents. It modulates a

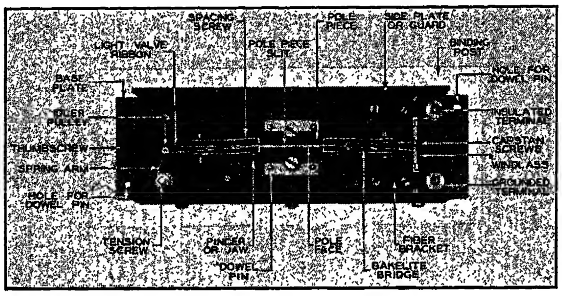

Fig. 15—Light Valve

light beam of constant intensity which is projected by means of the lens system on to the film, thus producing a film record of variable density.

The image of the light valve aperture is projected on to the film half size, so that it appears on the surface of the film in an unmodulated state as a line 1 mil wide and 128 mils long.

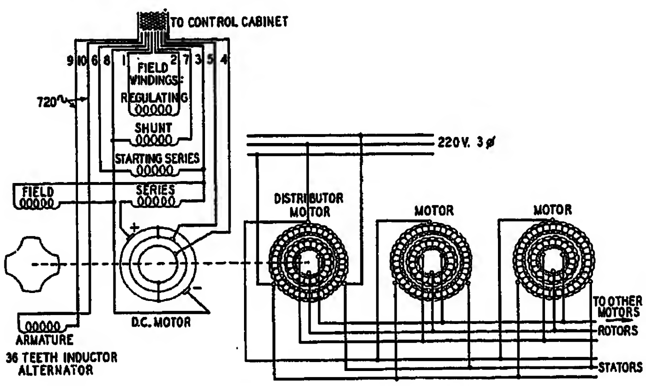

Fig. 16a—Schematic Diagram of Motor System

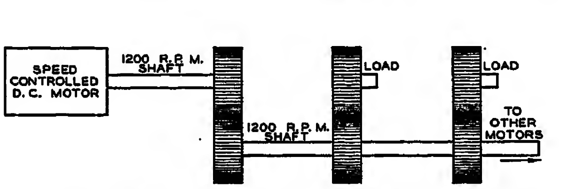

Fig. 16b—Mechanical Analogy of Motor System

The interlocking[6] of the motor system employs a principle known for many years in the electrical power field. It consists of connecting the stators and wire wound rotors of polyphase slip ring induction motors with similar electrical impedance characteristics, in parallel, and the placing of an alternating voltage across the stator. Each motor acts as a transformer. The rotors of all driving motors are brought into the same electrical phase relation as is presented by the distributor motor. This system gives a strong interlocking action between all motors. Mechanical rotation of the distributor rotor produces a corresponding rotation of all other interlocked rotors. Hence, if the rotor on the distributor is driven at a constant speed, all interlocked motors are likewise driven at the same speed independently of the power supply frequency and the actual number of revolutions from start to stop is exactly the same for all motors. (See Fig. 16a.)

The system may be thought of as a long shaft (see Fig. 16b) with all loads geared directly thereto. The shaft is then driven by the distributor motor at a constant speed and all loads will then run in synchronism

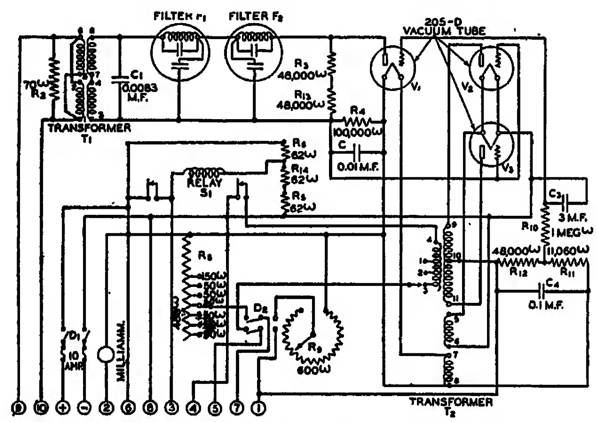

Fig. 17—Schematic Diagram of Speed Control Circuit for D-C. Motor

and likewise have the same number of revolutions from start to finish.

This feature of having the same number of revolutions from start is rather an important one. It permits the marking for synchronization of the sound film and picture film while stationary while still having complete synchronization throughout, and is also important in the transferring of the sound record from one film or disk record to another film or disk in a "dubbing" process.

Accurate speed control for both the recording and reproducing of sound films is required for all types of sound pictures. It is well known that the musical pitch varies directly with frequency and, therefore, in order that the reproduced sound may have the same pitch as the original, the record or film must run at an assigned constant speed.

The control cabinet (see Fig. 17) is the means for obtaining the constant speed of 1200 rev. per min. All recording and reproducing equipment is driven by 1200 rev. per min. motors. Referring again to the two drawings, Fig. 16 and Fig. 17, the driving unit is a compound

5. For a more detailed discussion, see "Sound Recording with the Light Valve," D. MacKenzie, *Bell System Tech. Jl.*, January, 1929.

6. For a complete discussion of the synchronizing and regulating methods used, see "Synchronization and Speed Control of Synchronized Pictures," H. M. Stoller, *Bell System Tech. Jl.*, January, 1929.

wound d-c. motor, which has, in addition to the regular series field, a special series field which is used to give extra torque at starting and is automatically cut out before the motor reaches full speed. It also has a shunt regulating field in which the current is governed by the vacuum tube control circuit. The motor is equipped with a small inductor generator which delivers 720 cycles to the control box at 1200 rev. per min. The armature winding of the motor is tapped at two opposite points, through slip rings; by this means 720 cycles

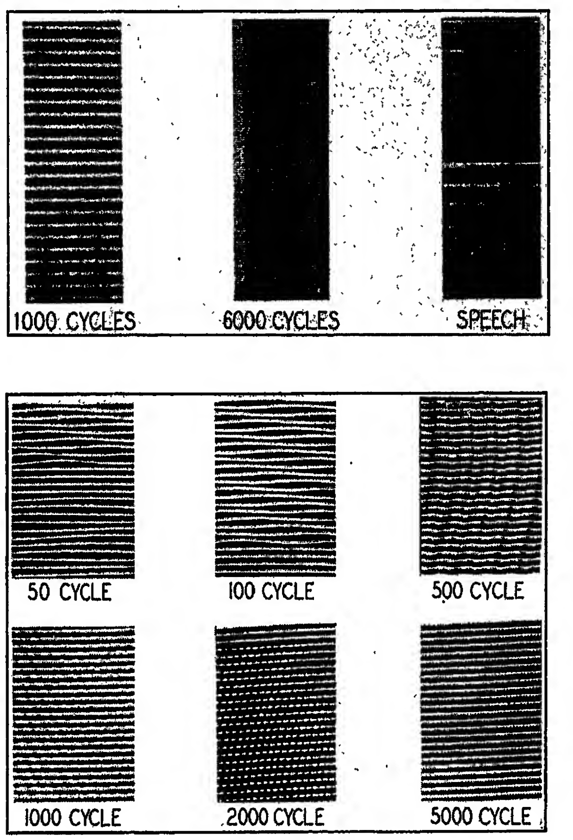

FIG. 18—TYPICAL FILM AND DISK SOUND RECORDS

a-c. is delivered to the control box for vacuum tube filament and plate supply.

The operation of the control circuit is governed by the low pass filters F_1 and F_2 with a 720-cycle cut-off. Below the cut-off frequency, a voltage is applied to the plate of tube V_1 which in turn produces a comparatively high negative potential on the grids of tubes V_2 and V_3 by means of the voltage drop across R_3. Hence the space current of V_2 and V_3 through the shunt regulating field is small and the motor speeds up. When up to speed (1200 rev. per min.) the 720-cycle current is regulated by the frequency cut-off characteristic F_1 and F_2 and the space current of V_1 is decreased which reduces the negative grid potential of V_2 and V_3. This permits a larger flow of direct current from V_2 and V_3 to the shunt regulating field and hence the motor slows down. In addition to the above controlling action, a feedback circuit for tube V_1 is provided. This circuit is made up of R_{10}, R_{11}, and R_{12} and C_3 bridged across the regulating field terminals, and gives a compensating action so that the speed is held within a fraction of one per cent.

The motor system is usually started and stopped by motor controls operated by the film recorder attendant in the recording room. When a "take" is about to be made the signal is received to "interlock." One phase of the 220-volt, three-phase power supply is closed, thus locking all the motors in a stationary position. Film in the cameras and film recorders is punched. A synchronizing start mark is also placed on the wax disk. Various colored signal lights controlled in the recording room, monitor room, and stage, when lighted indicate that all is in readiness. The system is started by closing the third wire of the three-phase, 220-volt power supply and the 110-volt d-c. supply for the d-c. distributor drive motor. A meter indicates when the system is up to speed and that the speed control is operating properly. When the motors are up to speed all operating stations receive a red bull's eye signal and the director starts the action. Red lights serve as a warning that recording is actually in process and that quiet must be maintained on the stage.

The wiring arrangement of the recording system provides full flexibility so that any stage may be connected to any recording room or amplifiers of one channel substituted for those of another. A dual set of storage batteries supplies filament and plate current to all amplifiers, recorder lights, and auxiliary equipment. A constant potential system of charging is used.

Maintenance routines similar to those employed in large telephone repeater stations have been found expedient. In this way any potential trouble hazard in the electrical system is anticipated since a failure during recording is very serious and expensive. The test laboratory is equipped with oscillators and suitable testing apparatus so that every channel may be tested daily before going into production.

SOUND PICTURE REPRODUCTION[7]

The introduction of sound into the motion picture theater has also necessitated changes. It has been necessary to redesign and rebuild the projection booths to take care of the special sound reproducing equipment. Towers have been built to support the horns behind the screen. In some instances theaters have been treated acoustically in order to improve the reproduction. Speech, music, and incidental sounds must be reproduced with fidelity in order that the effect be realistic.

A typical installation layout for talking motion pictures, as shown in Fig. 19, consists of: (1) film and disk

7. The sound reproduction system used in theaters will be discussed only briefly, on account of the rather complete description given by E. O. Scriven in *Bell System Tech. Jl.*, January, 1929, "A Sound Projector System for use in Motion Picture Theaters."

reproducing attachments, by means of which small electric currents are generated with variations corresponding to the sound waves produced in recording, (2) vacuum tube amplifiers which greatly magnify these electric currents, and (3)sound projectors consisting of receivers and horns which convert this electric energy into sound.

Sound film is run through a standard projector modified by the addition of the sound reproducing at-

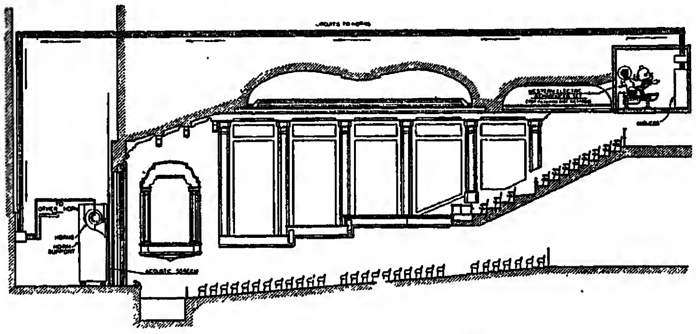

FIG. 19—THEATER CROSS SECTION SHOWING SOUND REPRODUCING EQUIPMENT

tachment. This is located between the head mechanism and the lower take-up magazine.

A light beam of high intensity is concentrated by an optical system containing a slit and focused to a fine line across the sound track of the film which passes through the sound gate. The film at this point moves with a uniform recording speed of 90 ft. per minute. On the film the sound record consists of a narrow margin (the sound track of Fig. 21).

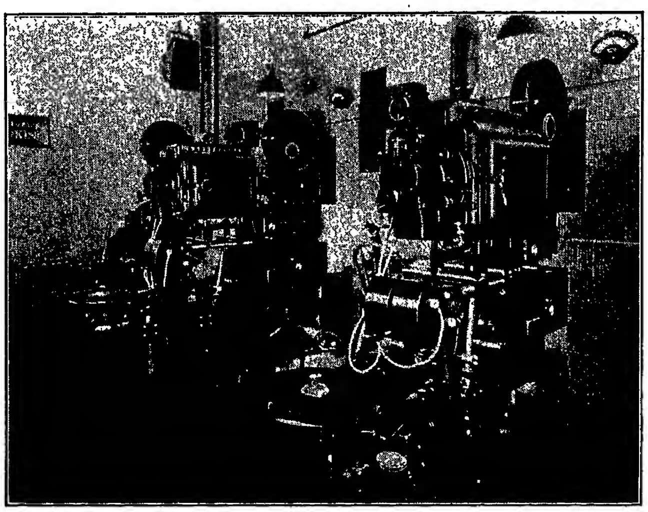

FIG. 20—PROJECTION BOOTH, SHOWING UNIVERSAL PICTURE PROJECTION AND SOUND REPRODUCING MACHINES

The spacing of the light and dark bands along this track determines the pitch of the sound, while the varying density determines the quality and the loudness, *i. e.*, the greater the contrast between light and dark bands, the louder the sound. On the other side of the sound gate and back of the film is a photoelectric cell which produces a small electric current with variations corresponding to the modulated light which strikes it. The photoelectric cell output is strengthened by a small amplifier built into the sound attachment and then carried to a fader which is used to control the sound volume during the showing of the film. From the fader the current is carried to an amplifier of size and power suitable for the theater, (Fig. 22). The output of this amplifier passes through a distributor panel to the loud speakers and horns located behind the screen from which the sound issues in synchronism with the picture.

FIG. 21—PICTURE AND SOUND ON SAME FILM—VARIABLE DENSITY METHOD

In the disk method of reproduction a current is generated by an electric reproducer playing on a disk record. The record is much larger than an ordinary phonograph record and revolves at 33⅓ rev. per min., thus enabling each record to play throughout a whole reel. The small electric current from the reproducer is carried to the fader where control is effected and thence to the amplifier and loud speaker system as in the film method.

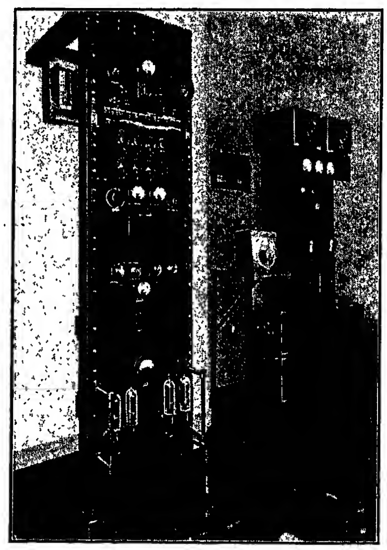

FIG. 22—THEATER AMPLIFIER EQUIPMENT

By using two projectors alternately, a continuous program can be run as with silent picture projection. This is accomplished by using the fader as a sound control at the same time that the changeover is made from one reel to the next. At the end of each disk or film record there is an overlap into the next, so that with proper operation the audience is unaware of any

change being made. Unlike silent motion picture projection where the film is generally projected at a faster speed than it was photographed, the sound picture must be shown at exactly the same speed at which it was made, or 90 ft. per minute. If a faster speed were used in reproduction, the pitch would be changed, causing the voice or music to be distorted. A constant speed is maintained by means of a special type of motor and a vacuum tube controlled electrical governing system similar to the distributor controlled system used in recording.

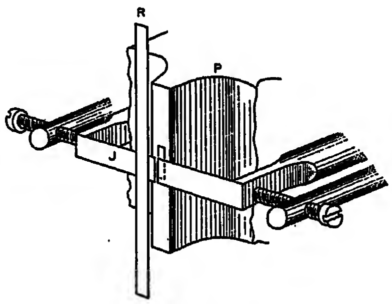

FIG. 23—THE PICTURE TRANSMISSION LIGHT VALVE

DEPENDENCE OF SOUND PICTURES ON OTHER ELECTRICAL ENGINEERING DEVELOPMENTS

The general processes involved in disk and film recording and reproduction have been discussed. From studio microphones to theater loud speakers the dependence of this new technique upon other electrical engineering developments has been heavy. Many kinds of apparatus, developed for other purposes, have been borrowed or adapted for use here, and many kinds of studies having other objects in view, have aided the commercial application of sound to motion pictures.

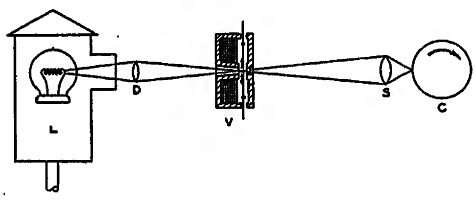

FIG. 24—PICTURE TRANSMISSION RECEIVING OPTICAL SYSTEM

We need but to survey the series of steps involved in the processes of recording and reproduction to see these relationships. Let us consider a few of the types of apparatus employed:

1. Microphones, or Condenser Transmitters. The condenser transmitter, as will be noted later, was developed originally in connection with studies of high quality telephonic speech. The transmission required for high quality studies does not differ greatly from that required for effective illusion in sound pictures. Originated by Mr. E. C. Wente,[8] the condenser transmitter comprised a substantial step beyond the earlier carbon microphones. While the latter are suitable for the commercial transmission of speech, they do not give the frequency range of transmission and the freedom from noise necessary in sound pictures.

Since the condenser transmitter is inherently an inefficient instrument, it has required to have closely associated with it a specially designed amplifier which increases the transmitter output but does not degrade the transmission nor introduce appreciable noise.

One of the most important uses to which the condenser transmitter has been put is in connection with experimental quality studies on speech and music. These studies will be referred to below.

2. The Light Valve. The light valve, also developed by Mr. Wente, has been adapted from the light valve used regularly in the commercial transmission of pictures over telephone lines.[9] The latter instrument uses but a single duralumin ribbon, the former a loop of duralumin ribbon of lighter weight. The smaller frequency range required for transmitting still pictures,

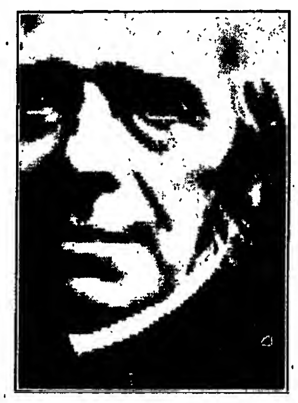

FIG. 25—PHOTOMICROGRAPH OF VARIABLE DENSITY TYPE PICTURES AS TRANSMITTED OVER TELEPHONE LINE

as compared with the transmission of high quality speech and music, accounts for the heavier construction permissible there.

Fig. 23 shows the picture transmission light valve, and Fig. 24 its arrangement in the receiving optical system.

Fig. 25 shows a photomicrograph of a portion of a picture of the variable density type produced by this valve and transmitted over a telephone line.

3. Amplifiers. The use of amplifiers for telephone, radio, public address, and other purposes is too well known to require much emphasis here. Suffice it to say that this type of apparatus has greatly altered practically all types of transmission systems for communication purposes. In sound picture recording, the currents derived from the condenser transmitters are so weak in comparison with those required to actuate a recording stylus or a light valve that amplification is

8. See "Electrostatic Transmitter," E. C. Wente, *Phys. Rev.*, May 1922, pp. 498-50

9. See "The Transmission of Pictures over Telephone Lines," Ives, Horton, Parker, Clark, *Bell System Tech. Jl.*, April, 1925, pp. 187-214.

vital. Not only this, but the many sources of noise which affect commercial recording systems would create very serious adverse effects if amplification of desired currents were not available. In this connection, it will be recalled that until the present electrical methods of phonograph recording were developed, it was found necessary to sacrifice quality of recording to obtain sufficient volume for phonograph reproduction. It is, moreover, amplification which makes possible the addressing of large audiences in the presentation of sound pictures in theaters.

For purposes of illustration, and as rough average figures, at a moment when the power of normal speech is about 10 microwatts, the power used to operate film

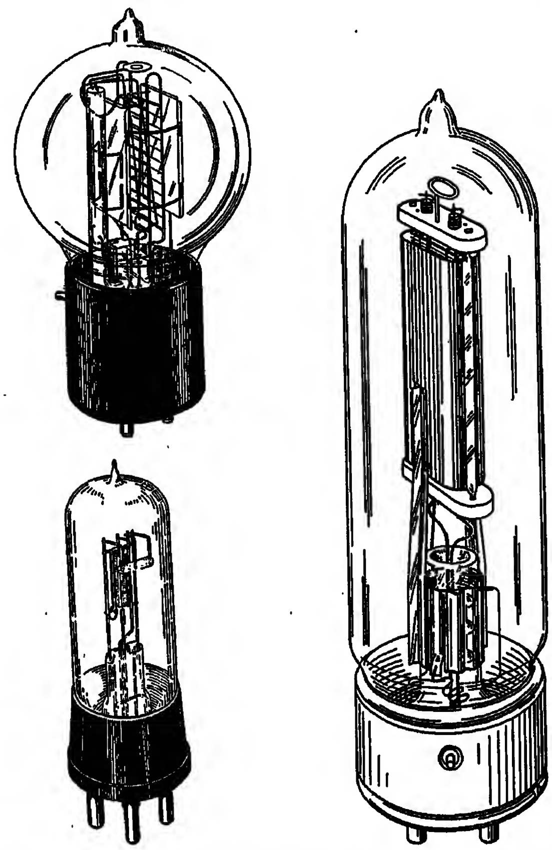

FIG. 26—VACUUM TUBES USED IN SOUND PICTURE SYSTEMS

and disk recorders would correspond to 0.006 and 0.018 watts, respectively; the power delivered by loud speakers in a large theater, however, would for the same conditions be about 2 watts.

Fig. 26 shows a variety of vacuum tubes used in various parts of recording and reproducing systems.

4. Loud Speakers. As in the case of amplifiers, loud speakers have already been widely used in telephony, radio broadcast reception, and public address reinforcement. The loud speaker was originally called "the loud speaking telephone" and differs from the usual type of receiver chiefly in power-handling capacity and frequency range transmitted. While there are various types of loud speakers available, the horn type has been adopted in Western Electric systems chiefly because of its high efficiency and large power-handling capacity, consistent with high quality reproduction.

In addition to these types of apparatus, there have been special incandescent lamps developed as light sources for the recording and reproducing systems, photoelectric cells have been employed in improved form, special motor systems have been used for synchronizing, regulated reproducer motors have combined vacuum tube technique with special motor design, monitoring circuit arrangements have been adapted from

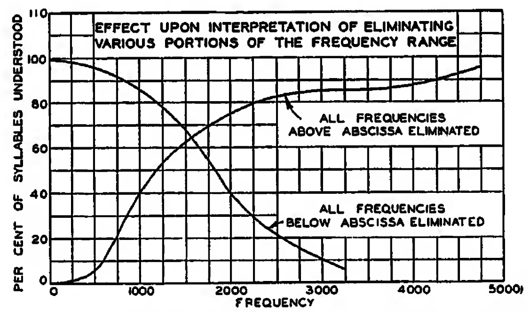

FIG. 27—RELATIVE IMPORTANCE OF DIFFERENT FREQUENCIES IN ARTICULATION

communication systems, signaling circuits have been suited to sound recording needs, mixing apparatus has grown out of that used for combining the output of public address and radio broadcasting microphones, and electrical test sets of various kinds have been designed for special purposes.

Almost innumerable research and engineering studies carried on in the communication field have influenced the design of sound picture apparatus and the manner in which it is used.

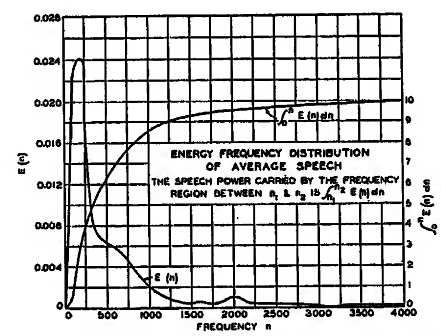

FIG. 28—DISTRIBUTION OF ENERGY OF AVERAGE SPEECH

Thus, extensive studies of the relative importance of different frequencies in speech from an intelligibility standpoint have been essential to the attainment of high quality transmission. (Fig. 27.) Likewise, measurements of the relative distribution of energy in speech and music have been important in estimating load-carrying capacities of apparatus and the magnitudes of interference currents between circuits (Fig. 28). Again, studies of the influence of various amounts of noise on the audition of speech and music have furnished design requirements on *quietness* in apparatus and circuits. In

this connection, it should be noted that in the use of commercial communication circuits, there is a continuous effort to reduce the interference to signal transmission from extraneous noises. Akin to the investigations just mentioned have been those (1) on the volume range of audition (Fig. 29), (2) on the average power of speech and music, (3) on the effects of overloading of vacuum tubes and other devices not entirely linear in their characteristics, and finally (4) on the effects of changing the pitch of speech and music.

With regard to circuits for transmitting frequency ranges, an extensive and well-developed art has grown

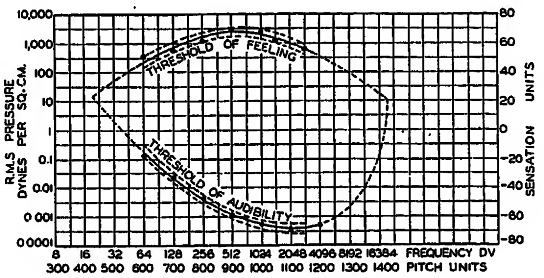

FIG. 29—VOLUME RANGE OF AUDITION

up in communication engineering which has been effectively applied to sound picture work. Examples of contributions from this source are (1) the method of comparing sound intensities by the use of power levels (Fig. 9) based on transmission units called *decibels*, (2) the method of *matching impedances* which secures optimum transmission, (3) the use of *gains* in amplifiers and *transmission losses* in mixing and other networks, (4) the method of avoiding resonances by annulling reactance effects over wide frequency ranges, (5) the method of designing high-frequency electrostatic shielding arrangements on a network basis, and (6) the correlation of mechanical, electrical, and magnetic vibrations by means of circuit analogs.

Other studies worthy of reference are those on magnetic materials (for example, *permalloy* used in transformers) and non-magnetic materials (for example, *duralumin* used in condenser transmitters and light valves), and studies of room acoustics and the properties of acoustic absorbing materials.

It may be observed that one of the most important reasons, in purely communication engineering, which led to the development of high quality recording and reproducing systems was in connection with laboratory studies of quality of transmission. For if in these tests the human element was to be eliminated, this could only be done by providing high quality records which might be used over and over again as sources of electrical currents to be analyzed. In such tests, likewise, the condenser transmitter and other high quality transmission devices were necessary.

Fig. 30 shows the various steps of recording and reproducing sound. These drawings indicate the rather unusual transformation which takes place during the interval from the picking up of the original sounds to their restoration in the theater. It is of considerable interest to trace these changes. Beginning as sound waves, mechanical motion is imparted to the diaphram of the condenser transmitter. This mechanical motion is in turn translated into a minute electric current. After being amplified the power of this current modulates a light to which film is exposed. The resultant latent image is treated chemically and when developed, again modulates a light to produce the positive. After development this positive, when run through a projector, modulates a beam of light, thereby controlling a minute electric current. After amplification the resultant power is sufficient to impart mechanical motion to a loud speaker diaphram, thereby producing a very close approximation to the original sound. Beginning as sound, fourteen changes of condition must be passed through before the sound is reformed. The same number of changes occurs in recording on disk.

GENERAL

The sound photoplay has revolutionized the work of the scenario writer, director, and actor and has been instrumental in building up large musical departments.

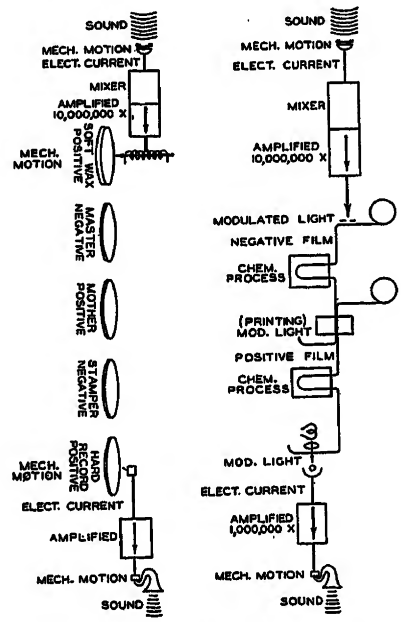

FIG. 30—RECORDING AND REPRODUCING SOUND, SHOWING INTERMEDIATE PROCESSES

In the days of the silent photoplay it was often the practise to schedule a feature almost before the story was written. During the actual photographing of the picture many thousands of feet of film were "shot" at random on large scenes in order to be sure that enough material would be available for the film cutters and editors to patch into a good story. Actors were directed so that the memorizing of lines was not important. With sound it has been necessary to thoroughly plan and re-

hearse each scene beforehand. Actors must memorize their lines and directors remain silent during the recording.

The director must broaden his artistic and dramatic efforts to include the new technical branch. Sound engineers with more electrical engineering experience than motion picture experience have found it necessary to adjust themselves to the new environment. These two different types of personalities have joined forces. To the motion picture producer, nothing is impossible. The entertainment value of a photoplay depends upon novelty and creative ability; consequently each new picture reveals some limitation of the recording system which must be surmounted. The sound equipment must be adapted to every conceivable use. Due to the characteristic methods employed in motion picture production and the financial resources of the industry, the future development of sound pictures is certain to be swift and far reaching. In this development the electrical engineer is certain to have an important place.

Discussion

D. H. Loughridge: In the design and development of the various units used in sound-picture reproducing channels it becomes essential to know the kind and magnitude of electrical distortions which enter at various points along the sound channel. In connection with work done in collaboration with Dr. R. C. Burt, I have found the cathode ray oscilloscope invaluable. This instrument utilizes the standard No. 224A cathode ray tube in such a manner that a linear time axis for frequencies from a single cycle up to 60,000 cycles is available. Changes from one frequency to another are simply accomplished by three toggle switches and two dials, the latter being a fine adjustment on the former. Adjustments are provided so that a wave, or waves, may be drawn out horizontally, or the zero line shifted vertically, horizontally, or diagonally so that any part of a wave may be moved to the optimum point of observation. Stabilization of the wave, in order to take photographs of it, is provided by a specially designed circuit controlled from the operating panel.

Using a rotating disk to modulate the light beam passing through a slit, its circumference cut so as to produce a polar sine wave, the question arises as to whether a certain photo cell gives out an electrical sine wave. The oscilloscope answers this question immediately when used in connection with a head amplifier which has previously been shown to be sufficiently free from distortion.

To work throughout the audible range, which is essential in talking motion-picture work, puts unsurmountable difficulties in the way of the Duddell type of oscillograph with its inherent resonant point within this range, but tests with standard oscillators have proved the ability of the cathode ray oscilloscope, when provided with a linear time axis, to work easily through this band of frequencies.

It has been found that in certain problems where practically no energy may be drawn from the source, the usual method of stabilization of the wave may require more energy than is available. In such cases a single stage of resistance-coupled amplification has been found to furnish the requisite stabilization so that the wave is perfectly stationary on the fluorescent end of the tube, with a very minimum of energy consumption.

Comparison and adjustment of phonograph pick-ups is also readily done by using constant-frequency records in conjunction with the oscilloscope. Distortions due to poor design or bad adjustment of this pick-up head are immediately apparent, and correction can be made without recourse to the doubtful test of the ear.

Dial Telephone System Serving Small Communities of Southern California

BY F. O. WHEELOCK[1]

Member, A. I. E. E.

Synopsis.—*This paper briefly reviews the history of the step-by-step dial telephone system in small communities of metropolitan areas and notes some of the reasons for its recent rapidly growing use in small towns and communities apart from metropolitan areas. The wider appreciation of improved service by the public in the last three years is noted and requirements of the service now being rendered are discussed. The equipment is described and the methods of operation and maintenance are given. The effect on outside plant, building design, and other related subjects are discussed as are also the results obtained in the use of this telephone system.*

* * * * *

INTRODUCTION

In rendering telephone service, two systems are in general use, the manual system and the dial system. The fundamental difference between these two systems, as the names imply, is that the principal central office operations for completing telephone calls are made by hand in the manual system, and are made by machine in the dial system. Dial telephone systems

FIG. 1—MAP OF SOUTHERN CALIFORNIA

are in use in a great many places today, largely in exchanges of considerable size with equipment arranged as a single unit having a capacity of ten thousand terminals or multiples thereof. The idea of providing telephone service by means of dial system equipment housed in small buildings and normally unattended for serving the small community is by no means new, but its use in this manner has been limited for reasons explained later on.

It is the purpose of this paper to describe the small step-by-step dial telephone system. A brief history is first given of its development, followed by a discussion of some of the considerations which led to its rather wide use in southern California. A description is then given of the equipment employed and its operation and maintenance. The exchanges specifically referred to are located in the area shown in Fig. 1.

1. Southern California Telephone Co., Los Angeles, Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., September 3-6, 1929.

FORMER EQUIPMENT OF SMALL EXCHANGES

In eight counties of southern California, prior to 1927, the number of offices and type of equipment used in providing exchange telephone service in the smaller towns were:

- 42 Magneto manual offices
- 20 Common battery offices
- 9 Semi-automatic offices (machine switching equipment controlled manually by means of operators)
- 4 Dial system (step-by-step) offices.

REASONS FOR ADOPTING PRESENT SYSTEM

More than fifteen years ago there were several small dial offices of the step-by-step type serving portions of the Los Angeles and San Diego exchanges. These were then known as "branch offices" and "automatic sub-offices." Each was in fact a part or an extension of the large dial office to which it was directly connected. Fig.

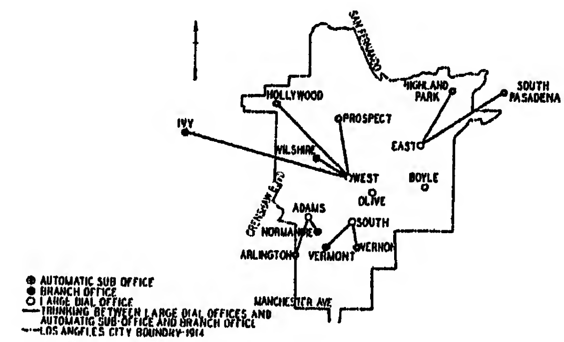

FIG. 2—MAP OF LOS ANGELES, SHOWING SMALL DIAL OFFICES IN 1914

2 shows the location of these offices in the Los Angeles exchange at that time. The branch office was fully attended and while the sub-office was smaller and was more of a complete unit in itself it also required rather constant attendance.

The endeavor to operate economically was probably the chief factor responsible for the establishment, years ago, of a 16-hour or 14-hour service day for the subscriber in the very small exchange. The recent growing demand for full 24-hour service in progressive communities, and an effort to secure greater economy and

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efficiency in giving better service were probably the motivating forces exerted in promoting, in 1926, the idea of using dial equipment for serving the small community with equipment operating independently of the larger or nearby exchange except for trunking and for trouble alarm signals.

A study was made in the latter part of 1926, and plans were formulated for installing a modern small dial telephone system in the rapidly growing new town of San Clemente, California. This was the beginning of the dial system program for serving small communities as discussed in this paper. Other installations have since been completed so that fourteen towns at the close of 1929 are similarly equipped. These are shown in Fig. 3 and include the following exchanges:

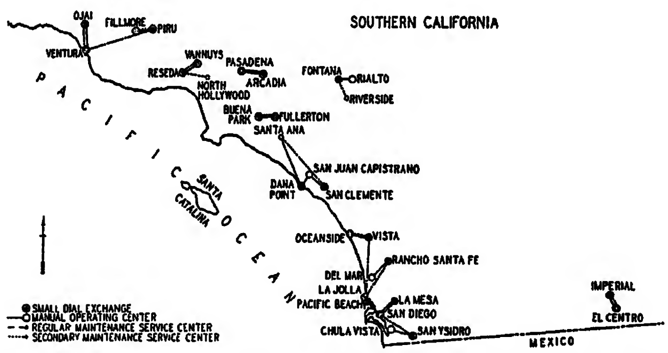

FIG. 3—SMALL DIAL OFFICES, MANUAL OPERATING CENTERS, AND MAINTENANCE SERVICE CENTERS

Arcadia	Pacific Beach
Buena Park	Piru
Dana Point	Rancho Sante Fe
Fontana	Reseda
Imperial	San Clemente
La Mesa	San Ysidro
Ojai	Vista

In addition to these, other small communities in the same area now served by the step-by-step dial telephone system, each of which includes some of the features described herein, are:

Artesia	La Habra
Barstow	Lynwood
Beaumont	Mar Vista
Bellflower	Norwalk
Downey	Palm Springs
Hynes	Rivera
Indio	Victorville

SERVICE REQUIREMENTS

A fundamental requirement in rendering universal telephone service is to have an operator readily available to the user in case assistance is necessary in completing a connection. This precludes the use of a telephone system that is mechanically operated in its entirety. In the small dial telephone system this feature is taken care of by operators located at a center serving usually more than one exchange.

The equipment requires routine supervision of its operation at various periods to insure satisfactory operation when called upon by the subscriber while dialing a number. It also requires attention to predetermine defects, potential and actual, that may cause trouble. From the standpoint of maintenance, therefore, it is also not entirely unattended.

Successful operation of a dial telephone system depends, in addition, upon a third human factor, the subscriber. The equipment may be designed, installed, and maintained properly with an operator readily available, but its operation will not be a success unless the subscriber uses his telephone properly. For this reason an early requisite in a dial system program is a comprehensive education of the public who are to use the dial station. The instruction is given the individual subscriber by experienced operators visiting them, and by installers when they are on the premises to install the new telephone. Pamphlets telling briefly how to use the dial telephone are also distributed to the subscriber as a part of the instruction program.

DESCRIPTION OF THE EQUIPMENT

The dial used at the subscriber's station in the small exchange of this system is marked in black with the ten numerals, 1 to 0. The word operator is also associated with the numeral 0.

The outstanding items of improved central office equipment used are as follows:

Line finders rather than line switches.

Self-protecting apparatus which permits of omitting heat coils in the battery supply leads.

Reverting call selectors.

10-Party code ringing connectors.

Choice of postpayment dial or postpayment manual coin box equipment.

Trouble alarm signals extending to the center from which the dial office is supervised.

Power plants with start and stop of charging current automatically controlled.

Ringing machines automatically controlled by selectors for the smaller exchange and continuously running for the larger exchange.

The picture in Fig. 4 shows, in the four rows of frames from left to right, connectors, line finders, local and incoming selectors, and toll selectors, respectively, with other central office equipment.

A complete central office consists of the following equipment:

Subscriber line equipment	Long line equipment
Line finders	Trouble alarm equipment
Selectors	Testing circuits and equipment
Connectors	Distributing frame
Repeaters	Relay rack
Coin box equipment	Power plant

The regular subscribers line equipment consists principally of line and cut-off relays. Dial coin box

subscribers line equipment consists of similar relays and associated equipment to furnish the necessary tone to indicate to the subscriber when to deposit a coin. Manual coin box subscribers line equipment consists of a concentrating switch of the rotary type to connect the line to a trunk leading directly to the manual operating center, and relays similar to those in the regular subscribers line.

The line finder, in appearance, is similar to an ordinary selector but in addition has a commutator and associated wiper for level hunting; it is a part of the call originating equipment and is used to connect the line of a calling subscriber to a first selector. Line and line finder equipment is arranged in units consisting of a maximum of 200 line and cut-off relays and a group of line finders and their associated banks. When mounted on 11-ft. 6-in. frames they are arranged three units of 200 lines each per frame in three sizes to mount 16, 20,

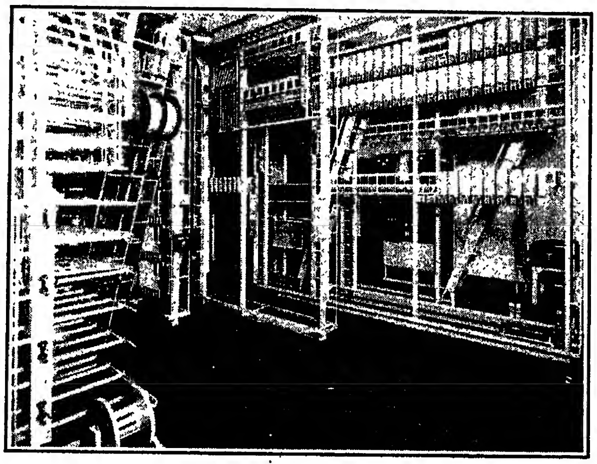

Fig. 4—Photograph, Interior View Showing Switch Equipment, Arcadia

or 30 line finders depending upon the amount of originating traffic. Partial units of any size and the required number of line finders can be installed to meet any requirement. Additions can readily be made without disturbing existing equipment. Frame heights less than 11 ft. 6 in. have been used and it is expected that another height of 7 ft. will be standardized for the lower ceiling heights.

Local selectors are of the usual two-wire type universally wired for local or incoming service. Toll selectors also are of the type used in the larger dial office. They are equipped with contacts that close with the vertical operation of the switch to operate a relay for controlling the start of the ringing machine in the offices where continuously run ringing machines are not employed.

Connectors are of the type used for the various classes of service, including:

One-bell
Two-bell
Rotary hunting
10-Party code ringing
Toll

Toll selectors and toll connectors are not provided where transmission is satisfactory over the local train.

Repeaters are of the usual type for the particular kind of trunk they are associated with, *i. e.*, one-way and two-way. One-way trunks are used principally in the larger offices where the volume of out of town traffic warrants separate trunk groups to handle the service in both directions. Two-way trunks are used where there is a small volume of out of town traffic. The two-way dial trunk at the manual center is arranged so that the operator may distinguish coin box calls from other local calls. This is accomplished by associating two lamps with each trunk, a red lamp which lights when a coin station is calling and a white lamp which lights when a flat rate station is calling.

Long line equipment consists of the usual relay, resistance, repeating coil, and condenser equipment to increase the normal impulsing and signaling range of the subscribers line.

The arrangement of the trouble alarm equipment includes visual and audible alarms which are extended to the adjacent manual operating center.

Ample testing equipment for all central office equipment and for subscribers line and station equipment is furnished.

Distributing frames are of the floor or wall type, the protector usually terminating the outside cable.

The relay rack is of the usual channel iron type. On it are mounted the long line, alarm, and other miscellaneous relay equipment.

The power plant includes storage batteries of either the portable or stationary type and arrangements for facilitating maintenance, such as automatic voltage regulators, Tungar rectifiers, ampere-hour meters for the automatic starting and stopping of the charging current, and ringing machines, either continuously running or those controlled by selectors. A picture of the charging equipment and ringing machines at Arcadia, California, is shown in Fig. 5.

When the present movement toward the wider use of dial equipment for the small community was started it was with a thought that the central office quarters could be provided at much less expense than for manual equipment by omitting operators' rest rooms, facilities for preparing lunches, etc. The ideal small dial central office equipment was pictured as a few self-contained units possibly divided between dial equipment, distributing frame, and power equipment, these to be of a rather portable type and installed in units as the office and community grew. It was suggested that this equipment might even be located so as to be on display

in windows of business places such as public garages, drug stores, or banks.

Up to this time, however, the equipment available has not been of a self-contained type. Use has been made of the standard 11-ft. 6-in. frames and racks, as in the large dial exchanges. Frames of a height 9 ft. 1¼ in. and 8 ft. 5¾ in. also have been used in some offices. These have required rooms with a fairly good ceiling height. It is expected, however, as previously mentioned, that within a short time there will be available an equipment using frames and racks limited to 7 ft.,

Fig. 5—Photograph, Interior View of Charging Equipment and Ringing Machines, Arcadia

together with self-contained units for the mounting of line finders, selectors, and connectors which will permit of installing equipment in rooms 9 ft. in height.

While in a few cases satisfactory rented quarters have been obtained, the majority of these dial offices are installed in company owned buildings which have been built expressly for housing the equipment. This has been done at a cost corresponding favorably with rented quarters. The arrangement and floor space occupied by the equipment for one of the exchanges is shown in Fig. 6.

Some of the earlier offices were not provided with heating apparatus. It has been found necessary, however, to place either gas or electric heaters in the majority of the small dial offices. These are regulated when in use by thermostatic control, and during cold or damp weather are operated continuously.

Method of Operation

On an ordinary call when a dial system subscriber removes his receiver the line finder automatically connects the line to an idle first selector. The subscriber hears the dial tone which indicates that he is connected to a first selector and that he may dial the number. The first digit of the desired number is dialed. The selector responding to the dial impulse is raised to the desired level, and finding an idle trunk cuts the line through to the connector. In offices where the total terminals exceed 1000, a second selector is inserted in the circuit between the first selector and the connector. With the dialing of the last two digits the connector steps up vertically and around horizontally until the dialed number is reached, at which time the ringing starts if the line is not busy. The ringing tone is heard by the calling party until the called party answers. If the line called tests busy a busy signal is heard by the calling party. Fig. 7 shows the path of the call for a completed connection. If the called number is on a 10-party line an additional digit is assigned. When this final digit is dialed a minor switch which is part of the connector operates in a rotating motion and upon completion of the dialing completes a circuit to relay equipment which sends out the required number of rings on the tip or on the ring side of the called line. The above method of operation is nearly identical with the method of operation in use in large exchanges where the line finder step-by-step type of equipment is employed.

Numbering plans, consisting of three and four digits, are used in the smaller exchanges and those of four and five digits are used in the larger exchanges. As previously mentioned, where code ringing is used the last digit indicates the code ring.

On out of town calls and assistance calls the subscriber dials "O" to connect with the operator at the

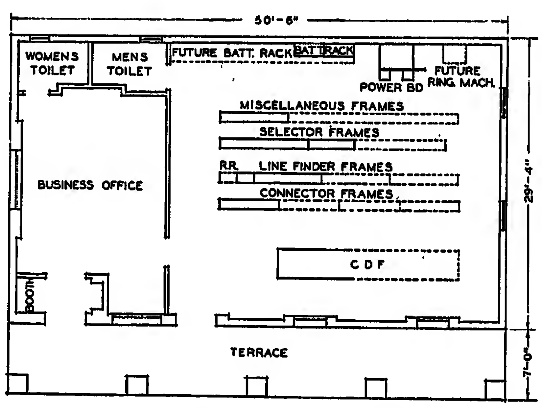

Fig. 6—Floor Plan, Ojai

manual center as shown in Fig. 8. The operator completes the call to the distant toll point. In handling assistance calls from the small dial exchange the operator may dial the desired number over the regular paths to test for busy or don't answer. No test connectors in the dial office are provided for verification and testing, so that the actual condition of the line in case it fails to connect through is not always known. Fig. 9 shows the path of an incoming call through the manual operating center to a dial system subscriber.

Where rotary hunting connectors are not provided,

private branch exchange service is given by listing all the trunk numbers in the directory. In most small dial exchanges no intercepting service is given for changed numbers, disconnected numbers, and vacant terminals; failure to hear the audible ringing signal is an indication to the subscriber that he has selected a vacant level or terminal.

Reverting calls, *i. e.*, calls to other stations on the same line, are obtained by calling a three digit number, first dialing nine then the last digit of the calling

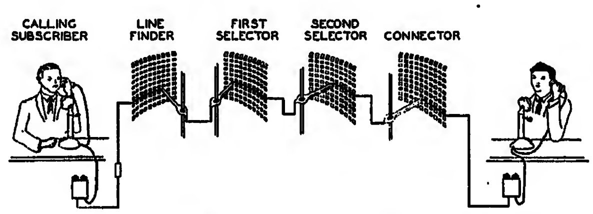

Fig. 7—Path of Local Call—Small Dial Office

subscriber's number, followed by the last digit of the called subscriber's number. The calling subscriber's receiver is then placed on the hook and the code ringing is received on the line. If the bell is on the same side of the line the called party's code ring is heard by the calling subscriber as an indication to him that the connection is completed; if the bell is on the opposite side of the line only the calling party's code ring is heard by the calling party. The ringing continues until the called party answers or it may also be stopped by the calling party removing the receiver from the hook. The reverting call switches are multipled in level No. 9 of the local first selectors.

No special provision is made for absorbing false pre-

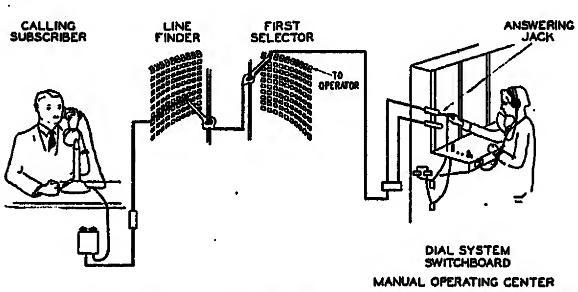

Fig. 8—Path of Call from Small Dial Office to Manual Operating Center

liminary impulses other than that level No. 1 of first selectors is not ordinarily assigned, but is used as a vacant level, initially.

Coin box stations are of the multi-slot postpayment type. Local numbers are dialed from dial coin box stations in the same manner as from any other dial station. When the called party removes his receiver from the hook a distinctive tone is heard by both parties which is an indication to the calling party to deposit a coin. When the coin is deposited the tone is removed, clearing the circuit and connecting it through for the conversation. This is accomplished with relay equipment that depends on marginal current for its initial operation, which releases by the momentary introduction of about 2000 ohms resistance in the station loop as the coin is being deposited.

Some service features of operation of ten of the small dial exchanges are shown in Table I. Length of trunks between small dial exchanges and manual operating center and the distances to the regular and secondary maintenance service centers are shown in Table II.

It has been possible, so far, to convert all magneto stations to dial stations. From the standpoint of economy and uniformity of operation and of equipment this arrangement is desired. Where it is not possible to make this change several methods of handling these stations are presented, such as selecting a trunk and signaling the operator by means of the subscriber's magneto, the operator then completing the call if within the local dial exchange by dialing back on the same trunk. Other bells on calling party's line are bridged and are called directly by the subscriber, the operator

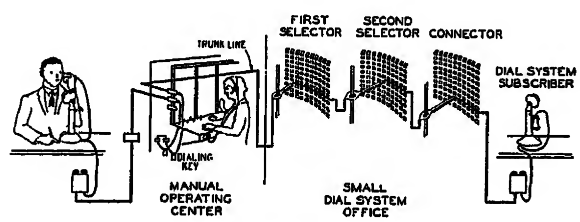

Fig. 9—Path of Incoming Call through Manual Operating Center to Small Dial Office

disregarding the signal on such calls. Another method is to provide a dial at the magneto station arranged for dialing over a simplexed leg to ground connected at the station, converting the impulses, by means of a repeater at the central office, to ordinary dial impulses.

Maintenance

In the operation of any telephone plant some maintenance effort is necessary to keep the equipment in good workable condition. The proper amount to give a good balance between maintenance effort and the quality of service rendered is desirable. In the larger central offices this is accomplished through systematic methods whereby the equipment is made to function on test on a somewhat more stringent margin than would normally be met with under the worst operating condition. Tests are made through the medium of test circuits designed to simulate the various conditions under which the apparatus is designed to function.

While the equipment specified for small dial offices is practically the same as that used in large dial offices and requires the same treatment, the amount of maintenance effort necessary to keep the apparatus functioning, due principally to the low calling rate, is considerably less than that required for the large office. The routine methods employed in a great many instances are

SERVICE FEATURES OF SMALL DIAL EXCHANGES

TABLE I

Exchange	1929 stations	Equipped capacity		Service		
		Lines	Terminals	2-Party terminal per station	4-Party semi-selective terminal per station	10-Party semi-selective code terminal per line
Vista	86	100	100	No	No	Yes
Piru	86	120	200	No	No	Yes
Rancho Santa Fe	88	120	200	No	No	Yes
Imperial	173	200	200	Yes	No	Yes
San Clemente	203	200	200	Yes	No	Yes
Reseda	296	300	400	Yes	No	Yes
Fontana	359	320	400	Yes	No	Yes
Pacific Beach	305	400	600	Yes	Yes	No
La Mesa	613	470	500	Yes	No	Yes
Arcadia	918	740	1200	Yes	Yes	Yes

Exchange	Treatment of		Postpayment coin service	Alarm service	Ringing current
	Vacant terminal and disconnect	Temporary disconnect			
Vista	1	2	Dial	4	On call
Piru	1	2	Dial	4	On call
Rancho Santa Fe	1	2	Dial	4	On call
Imperial	1	2	Dial	4	On call
San Clemente	1	2	Dial	4	On call
Reseda	1	2	Dial	4	On call
Fontana	1	2	Dial	4	On call
Pacific Beach	Intercepted	Intercepted	Manual	5	Continuous
La Mesa	1	2	Manual	5	Continuous
Arcadia	3	3	Manual	5	Continuous

1 No audible ringing signal. Subscriber is instructed to dial "0" to verify call when no ringing signal is heard.
2 Bell circuit is opened at station on 4-and 10-party lines. Jumper is lifted on connector terminal on 1 and 2-party lines with results as outlined in 1 above.
3 No audible ringing signals on local calls. Results as outlined in 1 above. Intercepted on toll connector groups only.
4 Alarms routed over regular trunk equipment.
5 Alarms routed over individual alarm circuit equipment.

TABLE II

Exchange	Miles to manual operating center			Manual operating center	Miles to maintenance service center	Maintenance service centers
	Wire	Cable	Total			
Vista	9.3	1.5	10.8	Oceanside	39.	La Jolla[1]
					10.8	Oceanside[2]
San Ysidro	8.1	1.	9.1	Chula Vista	17.	San Diego
Dana Point	...	5.	5.	San Juan Capistrano	30.	Santa Ana
Piru	7.8	.3	8.1	Fillmore	35.	Ventura[1]
					8.1	Fillmore[2]
Rancho Santa Fe	6.7	.9	7.6	Del Mar	18.	La Jolla
Imperial	4.4	.4	4.8	El Centro	4.8	El Centro
San Clemente	7.4	.4	7.8	San Juan Capistrano	33.	Santa Ana
Buena Park	..	4.5	4.5	Fullerton	4.5	Fullerton
Reseda	..	5.8	5.8	Van Nuys	4.5	Van Nuys[1]
					9.9	North Hollywood[2]
Fontana	..	4.	4.	Rialto	20.	Riverside
Ojai	3.8	11.2	15.	Ventura	15.	Ventura
Pacific Beach	..	12.1	12.1	San Diego	6.	La Jolla
La Mesa	..	12.1	12.1	San Diego	11.	San Diego
Arcadia	..	8.	8.	Pasadena	8.	Pasadena

1. Regular maintenance service center
2. Secondary maintenance service center

identical, but include some special tests for apparatus peculiar to this type of equipment.

The frequencies with which these tests are made are so arranged and scheduled that each piece of apparatus is routined periodically in proportion to the importance in which it functions. The testing equipment consists of three test sets as follows: a combination line, selector, and connector test set for testing adverse line conditions outside and inside the central office such as crosses, grounds, opens, etc., an interrupter machine for simulating dial impulses under extreme circuit conditions, and a line finder test set used in conjunction with a test panel located on the line finder frame.

In addition to routine testing the trouble signals and alarms provided facilitate maintenance of the equipment. The signals are in some cases concentrated and mounted in panels and in others they are located adjacent to the particular apparatus involved. The alarms generally are arranged individually at a central point to facilitate observance by the maintenance man. In addition to the office alarm equipment the alarm signals are made common and are routed over trunks or

individual circuits to the operating center to inform the operator of trouble during periods when no one is present at the dial office.

Visits to the small dial office by the maintenance men for the purpose of making routine operations and observations of the equipment were first scheduled weekly. Later it was found possible, without causing service reactions, to extend the frequency so that the minimum period between visits is two weeks. For the Reseda exchange the equipment routines require the attention of a central office repairman for about five hours every two weeks. The number of cases of trouble recorded, as a result of routine tests, has been negligible considering the amount of equipment involved.

One of the outstanding things that has been noticed is the adaptability of the central office and outside repair men who have been trained and have had their experience principally in the manual system, to quickly handle the equipment of the step-by-step dial system. The men are trained in advance of placing the new type of equipment in service in schools where maintenance problems are studied. The man who is to care for the office usually works with the installer while the central office equipment is being placed, and thereby gains valuable practical information in testing, clearing trouble, adjusting relays, etc.

Results Obtained

Some of the results obtained that have caused additional study and action as well as those that are favorable are recorded in what follows.

Outside Plant. Some trouble has been experienced from low insulation on open wire trunk circuits which are in operation between San Clemente and San Juan Capistrano, a distance of approximately 7½ miles. This trouble occurs only in dry climates where there is considerable dust accumulation and where rains are not sufficiently frequent to keep the insulators washed clean. Salt spray on the insulators from the ocean which is nearby also aggravates the situation. This condition has been under careful observation and has been tentatively taken care of by scrubbing the insulators with brushes and water at intervals. In washing insulators it is important that the under sides of the petticoat as well as the outside of the insulators be clean. The cleaning has been done with the insulators in place. This is a temporary means of taking care of the situation and has had to be repeated. It is felt, however, that the experience gained in studying the matter has been valuable. While final conclusions have not yet been reached as to the most practical way to permanently take care of this condition, it is thought that the installation of cable for a portion or the entire distance may be warranted.

At Fontana, one of the small communities first provided with dial equipment, rather serious service conditions existed during the first few months of operation due to various outside plant conditions. Winds of great velocity are frequent and several of the open wire leads pass through trees. These lines swinging together operated line finders nearly continuously, causing unnecessary wear and at times tied up the available paths for traffic in the office to an unsatisfactory degree. This condition was met by rather extensive rebuilding of outside plant and the service has been improved to a grade comparable to that of large dial offices. While these conditions were known before cutover they were carefully observed afterwards, and the experience gained resulted in first hand information as to what the limits in outside plant were, in order to render satisfactory service. In general the small dial system does not require any better grade of outside plant than the manual system. Conditions such as existed at Fontana were more of a deferred maintenance nature and ordinarily would have been corrected earlier under manual operation.

Buildings. The introduction of the small dial office has involved the construction of many new buildings for

Fig. 10—Photograph, Exterior View of La Mesa

the small exchange which has offered an opportunity to improve their appearance. Considerable thought has been given towards beautifying the outside as well as the inside of the structure. These small dial exchange buildings are scattered over a wide area and all conditions of topography and climate are met. Some are located in the hills, some near the ocean, and one in the Imperial Valley where extreme climatic and dust conditions exist. Figs. 10 and 11 are exterior and interior views of the exchange building at La Mesa.

Simplicity of Equipment. The avoidance of a multiplication of refinements in service and in ways of performing one and the same service are essentials to be kept in mind and closely controlled in the continued success of the small dial system. An open-minded public and company, both ready to waive the unessentials for the essentials, have made it possible to omit in most cases, features, such as intercepting service on unconnected terminals, to permit of simplification of the plant.

The small dial system must give satisfactory service at low cost and a careful course must be pursued to keep down the investment to permit of operating economically. Advantage has been taken of past experience in regard to providing the features that have proved most essential and to keep out of the design those that are unnecessary.

Experience at Piru. A brief résumé of the operation of the small dial exchange at Piru, California, immediately following the Santa Clara River Valley flood which occurred at midnight on March 13, 1928, is of interest.

On March 1, 1928, a small dial telephone exchange was placed in service at Piru with approximately 50 stations including three public coin box stations located, one in a hotel, one in a drug store, and another in an oil service station. The toll business was handled over

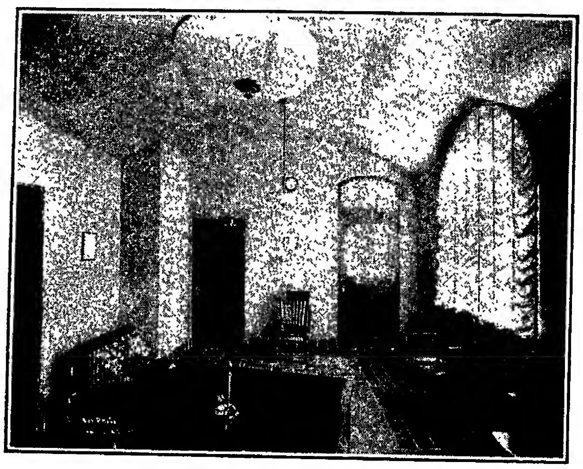

FIG. 11—PHOTOGRAPH, INTERIOR VIEW, COMMERCIAL OFFICE, LA MESA

four two-way trunks which terminated at the manual center at Fillmore, about eight miles distant.

Shortly after the dam broke and the waters had reached Piru a repairman visited the office and cleared the "permanents" which totaled three; the main part of the town being on high ground was not affected by the flood. From that time on, Wednesday until the following Saturday, the exchange was given special attention in order that any equipment or operating difficulties might be immediately corrected and also to observe how an exchange of this kind would function under these circumstances. Observations were made day and night. The power was off for about eight hours immediately following the disaster and this necessitated overcharging the batteries as soon as the power was restored. It was also necessary to watch the charge rather closely as there was a slight fluctuation in the power and it was thought advisable to keep the batteries fully charged in case of another failure. However, the batteries were at no time down to the danger point or the voltage below that required for the proper operation of the equipment. From March 14 to 17, the traffic was extremely heavy and several times the equipment and trunks carried an overload, due to the number of calls originating for assistance from the flood in the stricken area. One of the four two-way trunks had a swinging cross which could not be cleared. This trunk could be dialed over but at times it was impossible to signal the operator. It was, therefore, used by the operator for dialing towards Piru. The remaining three trunks gave no trouble.

The calls to Piru were closely supervised and the equipment thoroughly inspected, but only one case of trouble was encountered, this being a failure of the ringing interrupter alarm due to a relay being out of adjustment. No service reactions were caused by this defect.

The number of toll calls during this four-day period constituted a load of approximately 300 per cent in excess of normal. It was absolutely necessary that a good grade of service be rendered as outside help was needed and transportation was extremely difficult owing to all but one bridge over the river being swept away.

The equipment functioned perfectly at all times and would have given a good grade of service with little or no attention, even under the adverse conditions.

Psychological Aspect. Visitors to these small offices who know of the quality of the service in these exchanges have commented that they are impressed with the fact that the doors were locked, yet they view in fitting surroundings as they enter, a clean nearly perfect machine which is functioning continuously with very little human aid to give this service.

Today, the maintenance man is sure in his own mind of what the equipment does and will do in the future; he, therefore, goes about his work expecting the proper performance of the system and it functions accordingly. Before experience was gained by actual use it was the natural thing for all to be looking for causes that would prevent proper operation. Now, however, skepticism is a thing of the past, the system has proved satisfactory, and its permanent use is assured. Pessimistic thought has changed to constructive suggestion which can only result in improvement.

Discussion

S. Rapp: Mr. Wheelock brought out that the dial system will give better service to the small community, which has always been a problem. There are one or two items, however, that lead the application of the systems. One is the matter of special service lines or farmer lines. Farmer lines, for example, are not readily adapted to dial operation as signaling on them is done by alternating current obtained from a magneto generator. Dial signals are pulsating direct current. Also, the trunks from the small community exchange to the main operating center require somewhat different design from those used in manual operation. They must be better insulated and additional trunks must be provided to care for special service and maintenance tests.

The community exchange dial systems are being housed in attractive, permanent quarters as contrasted to rented quarters frequently used for manual systems. They have been established at four points in the Northern California and Nevada area, namely, Mountain View, Woodside, and Moraga in the San Francisco Bay area and at Sparks, Nevada.

Parallel Operation of Transformers
Whose Ratios of Transformation are Unequal

BY MABEL MACFERRAN*
Associate, A. I. E. E.

Synopsis:—*An equation is developed for use in meeting emergency conditions which necessitate the paralleling of transformer banks whose impedances expressed in percentage form are not equal. This equation makes it possible to calculate what change should be made in the ratio of transformation of the bank with the lower percentage impedance in order to prevent its being overloaded when the total load approaches the combined capacity of the two banks. It is pointed out that such an expedient is a makeshift justifiable only when maintenance of service is the paramount consideration and efficiency is, for the time being, of secondary importance. When conditions arise which do justify such a temporary arrangement, the method developed in the present paper affords a simple, yet accurate, means of solving the problem.*

* * * * *

Introduction

EMERGENCIES sometimes arise in which it becomes desirable to operate in parallel transformer banks whose characteristics are not ideally suited to such a procedure. It is well known that unless the impedances of the two banks, expressed in percentage form, are approximately equal, one bank will assume too much load in proportion to its rating, the other too little. The question then arises, whether it is possible so to change the ratio of transformation of one bank that under the most severe load conditions which are to be imposed on the combination, neither bank will be overloaded.

The purpose of the present paper is to derive an equation whereby the change in ratio necessary to accomplish the desired result may be calculated. Such an equation is very much needed, as the only method which, to the writer's knowledge, is now extant for attacking the problem is based on the regulation curves of the two banks and involves errors which make it somewhat inaccurate in many cases.

It should be clearly understood that the expedient of changing the ratio of transformation of one bank relative to that of the other is not being advocated as a permanent measure, as it results in marked inefficiency of operation. It is justifiable only as a temporary

FIG. 1—TRANSFORMERS OF UNLIKE RATIO IN PARALLEL OPEN-CIRCUIT CONDITION

step to be adopted under emergency conditions which require a certain peak load to be carried no matter what the cost in efficiency at lighter loads.

Fundamental Equations for Parallel Operation

The discussion will be based on the simple case of two single-phase transformers in parallel, since the principles governing the parallel operation of two three-phase banks are exactly the same as those governing the parallel operation of two transformers in a single-phase circuit.

It will be assumed throughout the discussion that the load is connected to the low-tension side of the paralleled transformers.

The fundamental considerations which control the behavior of two transformers operating in parallel are very simple. They are:

1. The voltage impressed on the high-tension winding of one transformer is equal to and in phase with that impressed on the high-tension winding of the other transformer.

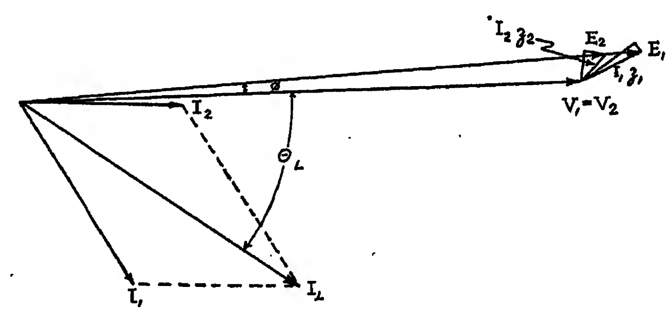

FIG. 2—TRANSFORMERS OF UNLIKE RATIO IN PARALLEL LOAD CONDITION

2. The voltage appearing at the low-tension terminals of one transformer is equal to and in phase with that appearing at the low-tension terminals of the other transformer.

From the first consideration it follows that the low-tension open-circuit voltages of the two transformers are in phase with each other.* The reason is that, neglecting the very small phase displacement caused by the exciting current, the low-tension open-circuit voltage of each transformer is in phase with the voltage impressed on its high-tension winding. The two low-tension open-circuit voltages are not equal in magnitude, however, unless the ratios of transformation are equal in the two transformers. The vector diagram

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*"Parallel Operation of Transformers," Waldo V. Lyon, *Elec. Wld.*, Vol. 63, No. 6, February 7, 1914, p. 315 ff.

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for open-circuit conditions is shown in Fig. 1. In this diagram, $\bar{E}_1$ represents the low-tension open-circuit voltage of Transformer 1, and $\bar{E}_2$ that of Transformer 2.

When a load is applied to the low-tension side of the paralleled transformers, the impedance drop in each transformer must be of such magnitude and direction that the second consideration is satisfied, as shown in Fig. 2.

In expressing these relations mathematically, the following symbols will be used:

$\bar{E}_1$ = low-tension open-circuit voltage of Transformer 1
$\bar{E}_2$ = low-tension open-circuit voltage of Transformer 2
$\bar{V}_1$ = low-tension terminal voltage of Transformer 1
$\bar{V}_2$ = low-tension terminal voltage of Transformer 2
$\bar{I}_1$ = current in low-tension winding of Transformer 1
$\bar{I}_2$ = current in low-tension winding of Transformer 2
$\bar{I}_L$ = current flowing to the load
θ_L = angle between load current and voltage impressed on the load.
ϕ = angle between voltage impressed on high-tension side of the transformers and voltage appearing at low-tension terminals
D = arithmetical difference between $\bar{E}_1$ and $\bar{E}_2$
Z_1 = equivalent ohmic impedance of transformer 1, referred to low-tension side
Z_2 = equivalent ohmic impedance of transformer 2, referred to low-tension side.

From Fig. 2 the following equations may be written:

$$\bar{V}_1 = \bar{E}_1 - \bar{I}_1 Z_1 \quad (1)$$

$$\bar{V}_2 = \bar{E}_2 - \bar{I}_2 Z_2 \quad (2)$$

$$\bar{V}_1 = \bar{V}_2 \quad (3)$$

The simultaneous solution of these equations gives:

$$\bar{E}_1 - \bar{E}_2 = \bar{I}_1 Z_1 - \bar{I}_2 Z_2 \quad (4)$$

Since $\bar{E}_1$ and $\bar{E}_2$ are in phase with each other, if $\bar{V}_1 = \bar{V}_2$ be selected as the reference axis we may write:

$$\bar{E}_1 - \bar{E}_2 = D \underline{/\phi} \quad (5)$$

Equation (4) may then be written as follows:

$$\bar{I}_1 Z_1 - \bar{I}_2 Z_2 = D \underline{/\phi} \quad (4a)$$

It is also necessarily true that:

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_L \quad (6)$$

Equations (4a) and (6), if solved simultaneously, give the following result:

$$\bar{I}_1 = \frac{\bar{I}_L Z_2 + D \underline{/\phi}}{Z_1 + Z_2} \quad (7)$$

$$\bar{I}_2 = \bar{I}_L - \bar{I}_1 \quad (8)$$

It should be noted that the use of the specific vector $D \underline{/\phi}$ in place of the general vector expression $(\bar{E}_1 - \bar{E}_2)$ ties Equations (7) and (8) definitely to $\bar{V}_1 = \bar{V}_2$ as a reference axis.

Equations (7) and (8) make it possible, given the difference existing between the ratios of transformation of the two transformers, to calculate the division of current for any specified total load. It must be borne in mind that *the solution will be correct for only the one load*, and that the currents will shift in relative magnitude and in relative phase position as the magnitude and power-factor of the load are changed.

It will be seen at once that there is one difficulty in the way of obtaining a direct solution for Equation (7). This difficulty is that the value of ϕ is not known until $\bar{I}_1$ and $\bar{I}_2$ are known, since the phase position of $\bar{V}_1 = \bar{V}_2$ depends on the magnitude and phase position of $\bar{I}_1$ and $\bar{I}_2$. Fortunately, this difficulty is of little practical importance, since the angle ϕ is usually so small that it may be set equal to zero with only a slight resulting error in the solution. If it is desired to carry the calculation to greater accuracy, the method of successive approximations may readily be applied. That is, ϕ may first be set equal to zero, the solution made, and the position of $\bar{V}_1 = \bar{V}_2$ calculated. Then with the value of ϕ obtained from this calculation, a new solution of Equation (7) may be made.

The impedances substituted in Equations (7) and (8) should be in the form of complex quantities, having both resistance and reactance components. The values used should be those applying to the taps on which the transformers are operating. This requirement will be found to offer something of a stumbling-block in practise, as the data ordinarily available give information only on the full-winding impedance values. It is beyond the scope of the present paper to discuss ways of estimating the tap values of impedance, other than to point out that as the transformer is placed on lower and lower taps, the impedance values referred to the winding on which the taps are situated generally decrease quite slowly, whereas the impedance values referred to the other winding *increase* rather rapidly. The exact mode of variation depends on the type of core, type of winding, and location of the taps. There is urgent need of published data on this subject. Such data being at present lacking, the engineer confronted with a problem in parallel operation must either rely on estimates based on his own experimental tests, or else neglect the variation of impedance with taps altogether. The latter course may be adopted if only an approximate solution is required.

If the problem at hand involves three-phase transformer banks, the application of Equations (7) and (8) is permissible providing the ordinary rules for working with one phase of a three-phase circuit are followed. In Appendix A will be found a more detailed discussion of this subject, with especial reference to the case in which one bank is delta-Y, the other Y-delta.

Ratio Change to Give a Desired Current Division

It is now easily possible to derive an equation which will give D in terms of the anticipated load current and the desired division of current between the transformers. It is only necessary to specify that:

$$\bar{I}_2 = \bar{A}\,\bar{I}_1 \quad (9)$$

In this relation, $\bar{A}$ is a vector quantity. Its magni-

tude will ordinarily be taken such as to make the ratio of the currents the same as the ratio of the transformer ratings. Its angle would *preferably* be zero, placing $\bar{I}_1$ and $\bar{I}_2$ in phase with each other; but it will be shown that it is not possible to specify *both* the magnitude and the angle of $\bar{A}$.

By substituting condition (9) in Equation (8), there is obtained the relation:

$$\bar{I}_1 = \frac{\bar{I}_L}{\bar{A} + 1}$$

Substituting this in turn in Equation (7), there results:

$$D \,\underline{/\phi} = \frac{\bar{I}_L (Z_1 - \bar{A}\, Z_2)}{\bar{A} + 1} \qquad (10)$$

Since D is by definition a pure arithmetical quantity, it is necessary that the expression on the right of Equation (10) come out as some quantity at an angle ϕ. In general, for a specified magnitude of $\bar{A}$ there is only one angle of $\bar{A}$ that will result in a vectorially correct solution to Equation (10). This means that it is possible to dictate the proportion between the currents $\bar{I}_1$ and $\bar{I}_2$, but it is not possible simultaneously to dictate the angle that shall exist between them.

The correct angle for the vector $\bar{A}$ must be found by trial and error. It is usually sufficiently accurate to assume ϕ approximately equal to zero. Then, having selected the desired magnitude for $\bar{A}$, it is necessary to try different angles for $\bar{A}$ until one is found which makes the right-hand side of Equation (10) come out to some quantity at an angle within two or three degrees of zero. D is then equal to this quantity. If greater accuracy is desired, the method of successive approximations may be applied to fix the value of ϕ more closely. However, in practical work it is not necessary to make an extremely accurate solution for D, because the anticipated load conditions are usually somewhat vague; and furthermore, there is seldom a tap available to conform exactly with the calculated value of D.

If D comes out positive, the open-circuit voltage of the transformer which was assigned the designation "2" is the one to be lowered, since Equation (7), from which Equation (10) is derived, is based on the assumption that $\bar{E}_1$ is greater than $\bar{E}_2$. If D comes out negative, then the open-circuit voltage of Transformer 2 is to be raised above that of Transformer 1. In starting out a solution, it is a good plan to assign the designation "2" to the transformer with the lower percentage impedance, because this will be the one whose open-circuit voltage will have to be lowered in order to prevent its taking too much load. Thus the inconvenience of working with a negative D will be avoided.

If the angle which it is necessary to assign to $\bar{A}$ in order to obtain a solution for D is of the order of 90 degrees or more, it is probable that the solution will be of little practical value, since even though the currents divide in proportion to the ratings, each will have to be so large (in order that their vector sum may equal I_L despite the large angle between them) that the transformers will in all likelihood be overloaded.

If it seems impossible to find an angle for $\bar{A}$ that works out satisfactorily, some other magnitudes for $\bar{A}$ will have to be tried. Of course there is no use trying magnitudes which differ markedly from the ratio of the ratings unless there is a very wide leeway between the load to be carried and the sum of the ratings of the transformers.

A minor difficulty presents itself in assigning the correct values to Z_1 and Z_2. Their values will depend on what taps are employed on the transformers, and these in turn will depend on the value of D. Here if desired the method of successive approximations may be applied. First solve for D, using the full-winding values of Z_1 and Z_2. Then if to obtain the required D it is necessary to place one or both transformers on taps, estimate the values of Z_1 and Z_2 on these taps and solve again for D. Repeat if necessary until little change occurs in D on the successive solutions. For practical work it is probable that the first value of D will be quite accurate enough, especially since the actual taps available may be such as to make it impossible to use the exact value of D obtained from the solution.

The reasonable procedure in attacking a practical problem is to make a solution for D, using the full-winding impedance values and assuming $\phi = 0$. Ascertain what taps come nearest to giving the required difference in ratio. Then assume the transformers placed on these taps and check the current division by Equations (7) and (8), using the values of Z_1 and Z_2 appropriate to the taps employed, and still assuming $\phi = 0$. Finally, when $\bar{I}_1$ and $\bar{I}_2$ have been found, check the value of ϕ by graphic construction or calculation, and if it differs from zero by more than two or three degrees, make a new solution based on this corrected value of ϕ.

In most practical cases the magnitude and power factor of the load are a little hard to predict. The best procedure is to select a value of D to fit the most severe load conditions which are anticipated. Then check the current division not only for this but for several other possible values of load and power factor, in order to be sure that there is no possibility of overload occurring on one of the transformers.

If D is selected to give the best possible current division conditions when the total load is of a magnitude approaching the combined capacities of the transformers, it will be found that as the load decreases the current vectors tend to swing further and further apart, until at no load they are 180 deg. apart and constitute a pure circulating current. On account of this increasing predominance of the circulating component at light loads, it is usually advisable to take the smaller transformer out of service when the total load drops to a value within the capacity rating of the larger transformer.

Conclusions

Equations have been derived which, for a specified total load at a specified power factor, determine the division of current between transformer banks which differ not only in impedance, but also in ratio of transformation.

A formula has been developed for use in meeting emergency conditions which necessitate the paralleling of transformer banks whose impedances expressed in percentage form are not equal. This formula makes it possible to calculate what change, if any, can be be made in the ratio of transformation of the bank with the lower percentage impedance in order to prevent its being overloaded when the total load approaches the combined capacity of the two banks.

It has been shown that when the ratio of transformation of one bank is changed in order to produce approximately correct load division under peak conditions, very inefficient operation results when the load drops below the peak value. Therefore, the expedient of ratio change is justifiable only when maintenance of service is the paramount consideration and efficiency is, for the time being, of secondary importance.

When emergency conditions arise which do justify a change of ratio, the method developed in the present paper affords a simple and yet accurate means of solving the problem.

Appendix A

Application of Equations to Three-Phase Transformer Banks

If the banks which are to be operated in parallel are both Y-connected on the low-tension side, Equations (7), (8), and (10) may be applied by using the low-tension line-to-neutral voltage and the impedance of one transformer in each bank. The currents to be used are the line currents flowing in the low-tension side of each bank and in the load.

If the banks are both delta-connected on the low-tension side, the equations may be applied by using the low-tension line-to-line voltage and the impedance of one transformer in each bank. In this case the currents to be used are the low-tension line currents divided by the square root of three.

If one bank is Y-connected on the low-tension side, the other delta, the simplest procedure is to convert the delta connection into a fictitious Y-connection which will have the same percentage impedance as the actual delta-connected bank. In order to derive an expression for the ohmic impedance of each transformer in the fictitious bank, it will be convenient to adopt the following symbols:

$\bar{V}_a$ = Rated voltage across low-tension side of each transformer in actual bank

$\bar{V}_f$ = Rated voltage across low-tension side of each transformer in fictitious bank

$\bar{I}_a$ = Rated current in low-tension winding of each transformer in actual bank

$\bar{I}_f$ = Rated current in low-tension winding of each transformer in fictitious bank

Z_a = Equivalent ohmic impedance of each transformer in actual bank (referred to low-tension side)

Z_f = Equivalent ohmic impedance of each transformer in fictitious bank (referred to low-tension side)

Since the actual bank is delta on the low-tension side, while the fictitious bank is Y, it follows that:

$$\bar{V}_f = \frac{\bar{V}_a}{\sqrt{3}}$$

$$\bar{I}_f = \sqrt{3} \times \bar{I}_a$$

$$Z_a = \frac{\text{Rated voltage} \times \text{per cent impedance}}{\text{Rated current} \times 100}$$

$$= \frac{\bar{V}_a}{\bar{I}_a} \times \frac{\text{Per cent impedance}}{100}$$

$$Z_f = \frac{\bar{V}_f}{\bar{I}_f} \times \frac{\text{Per cent impedance}}{100}$$

$$= \frac{\bar{V}_a}{\sqrt{3} \times \sqrt{3} \times \bar{I}_a} \times \frac{\text{Per cent impedance}}{100} = \frac{Z_a}{3}$$

That is, if the equivalent ohmic impedance (referred to the low-tension side) of each transformer in the fictitious bank is taken equal to one-third that of each transformer in the actual bank for which it substituted, the per cent impedance of the fictitious bank will be the same as that of the actual bank. The same reasoning applies, of course, to the resistance and reactance components of the impedance.

When the calculation of equivalent ohmic impedance referred to the low-tension side is based directly on data giving the per cent impedance of the transformer, the ratio of transformation does not enter the problem, and so it makes no difference whether the high-tension winding of the fictitious bank is Y or delta. However, the ratio of transformation does enter the calculation when it is desired to ascertain the taps to give a specified value of D. Here it is necessary to remember the rules as to what types of three-phase connection can and cannot be paralleled, in fixing the ratio of transformation of the fictitious bank. For example, if one bank is Y-Y and the other delta-delta, the fictitious bank which replaces the delta-delta bank must be Y-Y, *not* delta-Y. Or, if one bank is delta-Y and the other Y-delta, the fictitious bank which replaces the Y-delta bank must be delta-Y, *not* Y-Y. The ratio of transformation of the fictitious bank should be fixed accordingly.

In Appendix B an example is worked out which illustrates the method of forming a fictitious delta-Y bank to replace an actual Y-delta bank.

Appendix B

Example of Solution for Ratio

Owing to an unexpectedly rapid increase of load in a

certain territory, it is anticipated that a 3000-kv-a. bank will soon be called on to deliver 4000 kv-a. unless given some assistance. A bank to operate in parallel with it has been ordered from the manufacturers, but meanwhile some temporary arrangement must be made. There is available a 1500-kv-a. bank of considerably lower percentage impedance. It is proposed to make a ratio adjustment such that the 1500-kv-a. bank will operate satisfactorily in parallel with the 3000-kv-a. bank during periods of peak load, with the understanding that the smaller bank will be taken off the line when the load drops to within the capacity of the larger bank. What will be the required ratio adjustment?

The data on the transformers involved are as follows:

Bank No. 1—Three 1000-kv-a. transformers

Impedance volts	= 7.67%
Impedance watts	= 0.813%
High-tension voltages	= 19,050—18,200—17,300
Low-tension voltage	= 11,500
Present connection	= 18,200/31,500 Y to 11,500 delta

Bank No. 2—Three 500-kv-a. transformers

Impedance volts	= 4.25%
Impedance watts	= 0.748%
High-tension voltages	= 33,000—30,800—28,600
Low-tension voltages	= 7000—6800—6600—6200
Present connection—To be decided on.	

It is clear that in order to parallel with Bank No. 1, Bank No. 2 will have to be connected delta on the high-tension side, Y on the low-tension side. Therefore it will be convenient to replace Bank No. 1 by a fictitious bank connected 31,500 volts delta on the high-tension side and 6640/11,500 volts Y on the low-tension side. The equivalent ohmic impedance of each transformer in this fictitious bank will then be calculated as follows:

Equivalent Impedance—fictitious Bank No. 1

Rated low-tension voltage per transformer

$$= \frac{11,500}{\sqrt{3}} = 6640 \text{ volts}$$

Rated low-tension current per transformer

$$= \frac{1,000,000}{6640} = 150.7 \text{ amperes}$$

Full-winding impedance referred to low-tension

$$= \frac{\text{Rated Voltage} \times \text{Per Cent Imp.}}{\text{Rated Current} \times 100}$$

$$= \frac{6640 \times 7.67}{150.7 \times 100} = 3.38 \text{ ohms}$$

As a check on the correctness of the above value for the impedance of the fictitious bank, the per cent impedance of each transformer may be calculated by the well-known formula:

$$\text{Per cent impedance} = \frac{\text{kv-a.}}{(\text{kv.})^2 \times 10} \times \text{ohms impedance}$$

$$= \frac{1000}{(6.64)^2 \times 10} \times 3.38 = 7.67\%$$

In order to find the resistance component of the impedance, the impedance watts are utilized:

Impedance watts = 0.00813 × 1,000,000 = 8130 watts

Resistance referred to low-tension

$$= \frac{8130}{(150.7)^2} = 0.358 \text{ ohm.}$$

Reactance referred to low-tension

$$= \sqrt{(3.38)^2 - (0.358)^2} = 3.37 \text{ ohms.}$$

Summarizing:

$Z_1 = 0.358 + j\,3.37 = 3.38 \underline{/83.5}$ ohms referred to low tension.

Equivalent Impedance—Bank No. 2

Rated low-tension voltage per transformer = 7000 volts

Rated low-tension current per transformer = 71.4 amperes

Full winding impedance referred to low tension

$$= \frac{7000 \times 4.25}{71.4 \times 100} = 4.17 \text{ ohms}$$

Impedance watts = 0.00748 × 500,000 = 3740 watts

Resistance referred to low tension

$$= \frac{3740}{(71.4)^2} = 0.733 \text{ ohm}$$

Reactance referred to low tension

$$= \sqrt{(4.17)^2 - (0.733)^2} = 4.10 \text{ ohms.}$$

Summarizing:

$Z_2 = 0.733 + j\,4.10 = 4.17 \underline{/80}$ ohms referred to low tension.

Conversion of Impedance Ohms to Tap Values

Bank No. 1 is operating on the 18,200-volt tap on the high-tension side, whereas the value of Z_1 calculated above, is for the full winding or 19,050-volt tap. Hence the impedance, reactance, and resistance should be converted to terms of the 18,200-volt tap. The transformers are of a type which is known by experience to obey the following rules in regard to impedance on different taps:

1. The equivalent ohmic reactance referred to the winding on which the taps are situated remains approximately constant over a fairly wide range of taps.
2. The equivalent ohmic resistance referred to the winding on which the taps are situated varies directly in proportion to the tap percentage.
3. The equivalent ohmic reactance referred to the winding on which the taps are *not* situated varies inversely as the square of the tap percentage.
4. The equivalent ohmic resistance referred to the

winding on which the taps are *not* situated varies inversely as the tap percentage.

In Bank No. 1, the taps are on the high-tension winding, while the impedance to be used in the calculations is referred to the low-tension winding. Hence rules (3) and (4) above should be applied:

$$X_1' = \left(\frac{19{,}050}{18{,}200}\right)^2 \times 3.37 = 3.69 \text{ ohms}$$

$$R_1' = \frac{19{,}050}{18{,}200} \times .358 = 0.375$$

$Z_1' = .375 + j\,3.69 = 3.71\,\underline{/85}$ ohms referred to low tension.

The ratio of transformation of each transformer in the fictitious delta-Y No. 1 Bank is $\dfrac{31{,}500}{6{,}640} = 4.75$. It is safe to assume that the ratio of Bank No. 2 will be greater than this, since No. 2 has the lower percentage impedance and so must have its open-circuit voltage lowered relative to that of No. 1. As a preliminary estimate, assume Bank No. 2 to be on the full winding (33,000-volt tap) on the high-tension side, and on the 6800-volt tap on the low-tension side. This will give a ratio of transformation of 4.85. Applying rules (1) and (2):

$$X_2' = 4.10 \times 1 = 4.10 \text{ ohms}$$

$$R_2' = 0.733 \times \frac{6800}{7000} = 0.712 \text{ ohms}$$

$Z_2' = 0.712 + j\,4.10 = 4.17\,\underline{/80.3}$ ohms referred to low tension.

Solution for D

Assume load = 4000 kv-a. at 0.75 power factor

Then $I_L = 200\,\underline{/-41.4}$

$$\text{Let magnitude of } A = \frac{\text{Rating Bank No. 2}}{\text{Rating Bank No. 1}} = \frac{1500}{3000} = 0.5$$

Try first an angle of zero for the vector $\bar{A}$

By Equation (10):

$$D\,\underline{/\phi} = \frac{200\,\underline{/-41.4}\,(3.71\,\underline{/85} - 0.5\,\underline{/0} \times 4.17\,\underline{/80.3})}{0.5\,\underline{/0} + 1}$$

$$= 133.3\,\underline{/-41.4} \times 1.64\,\underline{/89} = 218\,\underline{/47.6}$$

This is not a solution, since ϕ must equal zero.

Try $\bar{A} = 0.5\,\underline{/+30}$

$$D\,\underline{/\phi} = \frac{200\,\underline{/-41.4}\,(3.71\,\underline{/85} - 0.5\,\underline{/30} \times 4.17\,\underline{/80.3})}{0.5\,\underline{/30} + 1}$$

$$= 136\,\underline{/-51.4} \times 2.08\,\underline{/58} = 283\,\underline{/6.6}$$

Try $\bar{A} = 0.5\,\underline{/+40}$

$$D\,\underline{/\phi} = \frac{200\,\underline{/-41.4}\,(3.71\,\underline{/85} - 0.5\,\underline{/40} \times 4.17\,\underline{/80.3})}{0.5\,\underline{/40} + 1}$$

$$= 140\,\underline{/-54.8} \times 2.38\,\underline{/53} = 333\,\underline{/-1.8}$$

This solution gives a value of ϕ very close to zero, and may therefore be adopted. It means that $\bar{E}_2$ must be made 333 volts lower than $\bar{E}_1$.

When the high-tension voltage is 31,500 volts, $\bar{E}_1 = \dfrac{31{,}500}{4.75} = 6640$ volts. Hence at the same time, $\bar{E}_2$ should be $6640 - 333 = 6307$ volts. This means that the ratio of transformation of each transformer in Bank No. 2 should be $\dfrac{31{,}500}{6307} = 5.00$.

The required ratio of 5.00 on Bank No. 2 can be obtained by placing each transformer on the 33,000—6600-volt taps.

Check of Correctness

To check the correctness of the solution, including the possible error due to not using exactly the right value of ϕ, Equations (7) and (8) may be applied.

The value of Z_2 should be changed to accord with the 6600-volt tap to be used on Bank No. 2. The new value will be

$$R_2'' = 0.733 \times \frac{6600}{7000} = 0.691$$

$$X_2'' = 4.10 \times 1 = 4.10$$

$Z_2'' = 0.691 + j\,4.10 = 4.16\,\underline{/80.7}$ ohms referred to low tension.

By Equation (7):

$$I_1 = \frac{200\,\underline{/-41.3} \times 4.16\,\underline{/80.7} + 333\,\underline{/-1.8}}{.375 + j\,3.69 + .691 + j\,4.10}$$

$$= 141\,\underline{/-54}$$

$$I_2 = 200\,\underline{/-41.3} - 141\,\underline{/-54} = 70\,\underline{/-17}$$

Checking the value of the angle ϕ by graphic construction or by calculation, it is found that $\phi = +2$ deg. The error introduced in the solution by taking $\phi = -1.8$ deg. is therefore negligible from a practical standpoint, and hence it is not necessary to make a re-calculation of I_1 using the new value of ϕ.

In checking the size of the angle ϕ it is also found that $V_1 = V_2 = 6180$ volts if the impressed high-tension voltage is 31,500 volts. Using this voltage as a basis for kilovolt-ampere calculations, it is found that:

Total kv-a. = 6180 × 200 × 3 = 3700 kv-a.

Bank No. 1 kv-a. = 6180 × 141 × 3 = 2600 kv-a.

Bank No. 2 kv-a. = 6180 × 70 × 3 = 1300 kv-a.

It is seen that the banks divide the kv-a. in proportion to their respective ratings, and that the sum of the kv-a. in the two banks comes to only 200 kv-a. more than the total load. This represents a wasted capacity of only 4.4 per cent of the total rating of the banks. Thus the operating conditions may be regarded as fairly efficient.

Had the two banks been operated with equal ratios of transformation, the kv-a. assumed by Bank No. 2 would have been roughly equal to

$$3700 \times \frac{3.38}{3.38 + 4.16} = 1660 \text{ kv-a.}$$

This exceeds the rating of the bank by 160 kv-a.

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Progress in the Study of System Stability

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Member, A. I. E. E. — Associate, A. I. E. E.

Synopsis.—In the second part of this paper and in the appendices attention is given to simplified methods of treating the problem of system stability. Methods are recorded which have been found useful in making many system studies. These methods have had considerable verification by tests both on a model system and on large operating systems and have been simplified to such an extent that many operating companies are now finding it to their advantage to undertake the work of making careful studies of their own systems, just as they now make short circuit studies which formerly were thought too difficult and too highly theoretical.

The first part of the paper gives some comments and conclusions of the authors and their colleagues as a result of many such system studies as well as studies involving more detailed methods, and also as the result of practical experience through contact with various operating companies. Some of these comments are based directly on an example which is given in detail in Appendix I.

INTRODUCTION

The literature on Power System Stability is growing rapidly.† It includes papers on theoretical methods of calculating stability, on observations of actual systems, and on methods of improving stability. This paper is intended to give the conclusions of the authors and their colleagues based on many careful system studies and on observations and tests on actual and model systems. Appendix I contains the results of some calculations to compare the theoretical performance of various assumed system connections. The economies of design are not considered as such in this paper. This phase may be readily introduced after the engineering facts have been obtained. Other factors enter in such as geological and local weather conditions. Thus the calculations given here are specifically recognized as being but one item in the problem, an important item nevertheless.

The appendices of the paper include formulas and calculations which have been found useful in making stability studies and which may be helpful in extending the usefulness of the paper.

The conditions under which instability occurs may be classified as:

Case 1. Under steady load conditions due to inadequate synchronizing power.

Case 2. Under steady load conditions due to hunting.

Case 3. During disturbances, particularly those due to short circuits.

Case 1. Various criteria have been developed to permit the design of a system which will be stable under these conditions.[1, 15, 21] Continuously vibrating regulators are helpful in increasing the power limit, especially when the machine synchronous reactances are a large percentage of the whole reactance. A power system must be stable under steady load conditions for a reasonable margin above the expected load to allow for some swings and hunting, otherwise the system will be liable to lose synchronism at any time. Therefore no system should be considered practical unless such a margin is established at the outset. Thus in practise, the problem reduces to the consideration of cases 2 and 3.

Case 2. This type of instability occurs principally at light loads and when the resistance of the lines involved is high. Continuously vibrating regulators are apparently helpful in eliminating danger from this cause.

Case 3. This is the type of instability which demands most attention today. Faults may be conductor-to-ground, conductor-to-conductor, two-conductors-to-ground, or three-conductors-shorted, in the order of their severity. Experience indicates that some systems are largely subjected to one-conductor-to-ground faults, while others are largely subjected to two-conductor-to-ground faults. The character of the fault, whether one-conductor or two-conductor-to-ground, has a decisive influence in the design of systems for stability at all times.

The effect of these faults is suddenly to throw an active and reactive load on the system and to reduce the synchronizing power between machines. As a result the position of the rotors of the machines in the system tends to vary, the variation being in general such as to increase the angular separation between the generators and motors.

An accurate analysis involves a step-by-step calculation of the motion of each machine in the system, the principle factors involved being the line reactances, machine synchronous and transient reactances, time constants of the machine field structures, governor and regulator actions, switching times, and machine inertias. Simplified methods of analysis in certain cases are available.* The examples in Appendix I of this paper have been chosen so that these simplified methods may be used, thereby making it possible to investigate a larger number of cases without unduly increasing the labor involved. Step-by-step calculations are also used extensively and a simple example of this method is given in Appendix IV.

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†See Bibliography.

Presented at the Pacific Coast Convention of the A. I. E. E., Santa Monica, Calif., Sept. 3-6, 1929.

1. For references see Bibliography.

*See Bibliography 1, and Appendices II and VIII.

Part I

The Relation of System Connections and Apparatus to Stability

As a result of many stability studies and also of practical experience the following comments have been prepared.

Apparatus

(*a*) *Generators*

(*I*) *Short Circuit Ratio.* High short circuit ratio is of benefit in improving the power limit under steady load conditions with hand control. The use of the proper kind of voltage regulators and excitation systems extends the power limit both under steady load conditions and under transient conditions† and may largely overcome the disadvantages of low short circuit ratio.

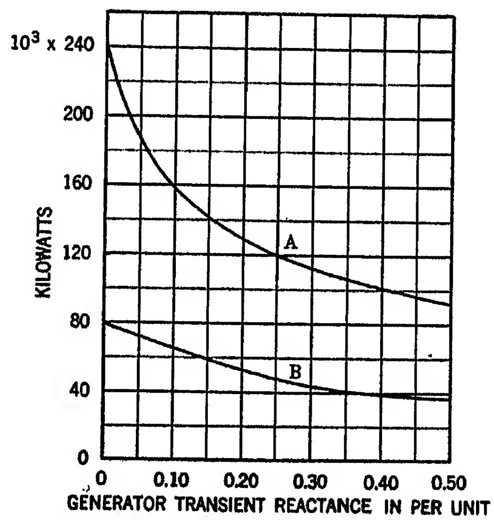


Fig. 1—Power which may be Carried through Fault Conditions outside Generator Transformers *Versus* Generator Transient Reactance when the Fault is Cleared in 1.0 sec.

For set up see Diagram A Fig. 4
A—1 conductor to ground fault
B—2 conductor to ground fault

How much dependence should be placed on regulator action is a question which is not yet settled. If no regulator is used or if no reliance is placed on the regulator action the short circuit ratio should be just great enough so that steady state stability is always insured for the most severe load condition anticipated, provided that line charging requirements do not predominate. On this basis it will often be found that a higher short circuit ratio is required than would otherwise be necessary, which results in a greater first cost and lower efficiency. Therefore, it is thought that an alternative basis may be acceptable, namely, that the short circuit ratio be only sufficient for steady stability under normal conditions. A regulator would then be used to maintain stability during short periods of overload such as might occur, for example, owing to the sudden loss of one generator in a system.

†See Figs. 4 and 5 of Bibliography 1.

(*II*) *Transient Reactance.* A low transient reactance is of benefit in improving stability under transient conditions (see Fig. 1) provided that the disturbances which are anticipated are not so severe that there is no possibility of holding in synchronism. Thus, with a given arrangement of lines and transformers, it may be found that there is ample stability for conductor-to-ground faults, but no chance of it under two-conductor-to-ground faults except when the generators happen to be operating at greatly reduced loads. In this case a reduction in transient reactance might be of little value. On the other hand, with a different system layout, a reduction in transient reactance may be necessary for stability even with conductor-to-ground faults or in still another case such a reduction may permit operation through two-conductor-to-ground faults. The proper value of machine transient reactance thus depends markedly on system layout and its determination involves a study of line and transformer as well as generator costs.

(*III*) *Damper Windings.* Damper windings have two effects: the first a damping action, the second an increase in fault current and shock to the system. The latter effect is due to the reduction in generator negative phase sequence reactance. If the shock to the system is relatively small a slight increase in shock, because of the reduction in reactance, will not be serious. If the shock is so severe that synchronism will be lost without damper windings, their presence cannot make matters worse. There will be a critical shock which is just great enough to cause instability when no damper

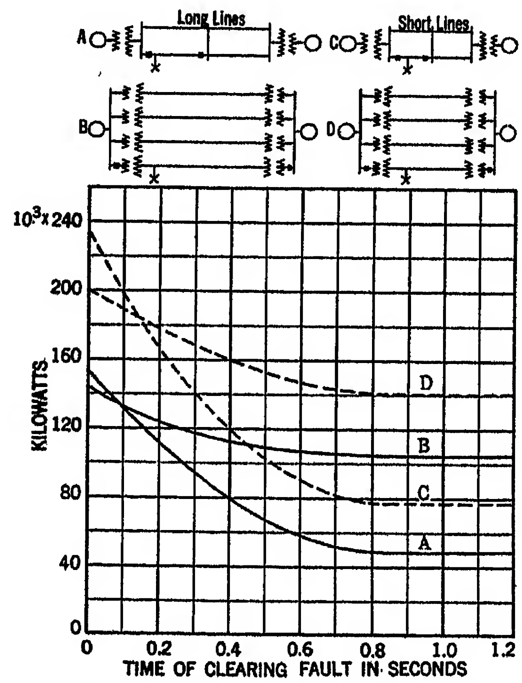


Fig. 2—Power which may be Carried Through a Two-Conductor-to-Ground Fault Outside the Generator Transformers *Versus* Time of Clearing the Fault.

——— Long lines
– – – – Short lines

winding is used. Calculations made on typical systems have indicated that with a shock of this magnitude the beneficial effect of damping exceeds the disadvantageous effect of increased shock. Furthermore, the presence of damper windings produces a markedly beneficial effect in extinguishing arcs more quickly due to the reduction in the recovery voltage. Therefore, the use of low resistance damper windings on water

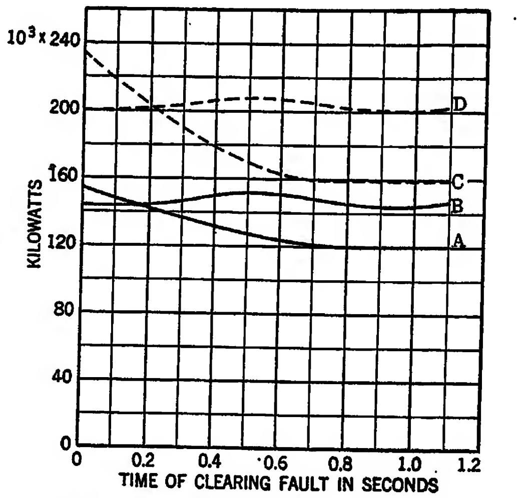


FIG. 3—POWER WHICH MAY BE CARRIED THROUGH A ONE-CONDUCTOR GROUND FAULT *Versus* TIME OF CLEARING THE FAULT

FOR DIAGRAMS SEE FIG. 2

——— Long lines
- - - - - - - Short lines

wheel generators would in general appear desirable. Such windings should be especially desirable in cases where stability is determined after several swings. Field tests are required to verify these data.

(*IV*) *Inertia.* The effect of inertia of machine rotors is to delay their swinging action. It is thus beneficial because it allows the circuit breakers to act at a point earlier in the swing. The benefit is limited, however, because the effect on stability of increasing the inertia everywhere in the system by a given ratio is only equal to the effect gained by decreasing the switching time by the square root of this ratio.* Also, the effect of the addition of inertia at one end of a line, for example the generator end, is only such as to make the inertia of the whole system approach as a limit the inertia of the other end of the line.† It would appear that inertia can only be economically obtained when it is secured in large quantities by means of interconnection.

(*V*) *Double Windings.* Double windings[17] are often a valuable feature when the interconnection of machines at generated voltage is desired. The principle involved is the use of the inherent reactance of the machines to limit the short circuit current.

*See Appendix VIII.

†Because in this case the equivalent inertia constant

$$M = \frac{M_1 M_2}{M_1 + M_2}$$

(*b*) *Excitation Systems*

It has been definitely shown that regulators which act quickly are effective in improving stability. For example, as stated above in paragraph (*I*) under generators, with proper regulators both steady state and transient power limits may be materially increased. To accomplish this result it is necessary that the excitation systems be fast enough to respond sufficiently. The practical criterion of the speed of response necessary has been investigated and a tentative figure of 200 volts per second determined.[1, 16] Field tests should be made on an actual system to verify this decision.

The use of the appropriate type of regulator also tends to prevent hunting.

(*c*) *Neutral Impedance*

The effect of neutral reactors is to lower the shock when faults involving grounds are considered.

For conductor-to-ground faults the benefit is very great, and it is considerable for two-conductor-to-ground faults also. Quick switching tends to reduce the gain due to reactors, but even with 0.2 second switching time they still have a considerable value. The improvements which may be expected from the use of neutral reactors are shown in Figs. 6 and 7.

The amount of neutral reactance is necessarily a compromise between gain in stability, reduction in circuit breaker duty, reduction in current available for actuating relays, reduction in telephone interference, and an increase in phase voltage to ground during disturbances.

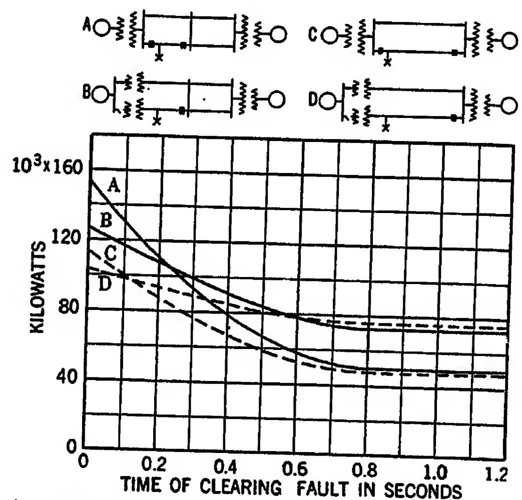


FIG. 4—POWER WHICH MAY BE CARRIED THROUGH A TWO-CONDUCTOR-TO-GROUND FAULT OUTSIDE THE GENERATOR TRANSFORMERS *Versus* THE TIME OF CLEARING THE FAULT

——— Long lines, mid-sectionalizing bus
- - - - - - - Long lines, no mid-sectionalizing bus
A and *C*...... High-voltage Buses
B and *D*...... Low-voltage Buses

The latter consideration becomes important in connection with lightning arresters and overvoltage relays. Studies have shown that when ground relays are used a reactor of about 2½ to 3 times the reactance of the transformer is usually correct. In cases of sufficient importance this figure should be checked by special cal-

culation. The neutral reactance so far discussed does not in any way approach the dimensions of a Petersen coil, and therefore does not involve resonance phenomena. The Petersen coil is merely a reactor which permits a reactive fault current equal to the line charging current to ground under fault conditions and this reduces the fault current to a low value.[3, 4] In addition, it operates to cause the voltage across the arc to recover slowly in case the arc is extinguished. When the arc extinguishes, both the voltage across it and the dielectric

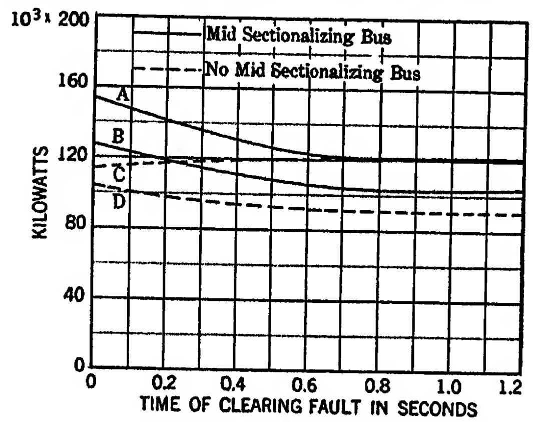


FIG. 5—POWER WHICH MAY BE CARRIED THROUGH A ONE-CONDUCTOR-TO-GROUND FAULT OUTSIDE THE GENERATOR TRANSFORMERS *Versus* TIME OF CLEARING FAULT (SEE FIG. 4 FOR DIAGRAM)

———— Mid sectionalizing bus
– – – – – No mid sectionalizing bus

strength of the arc space begins to increase. The arc will extinguish permanently if the recovery voltage across it is always less than its dielectric strength.[34] Thus the magnitude of recovery voltage is a measure of arc stability. The magnitude of the recovery voltage in the first ¼ cycle depends on the degree of "tuning" and is proportional to the ratio of fault current with the Petersen coil to the fault current without the Petersen coil. Even with only a moderate degree of tuning this ratio is small and experience shows that even on widely distributed systems with large charging currents, the arc is unstable and goes out. Petersen coils are much used abroad, but have so far been little used in this country. Experience abroad would indicate that their use here should be reconsidered.

Neutral resistors may be of two types: current limiting and braking. The former is of relatively high resistance and acts primarily to reduce the shock to the generator and the system having the fault. The latter is of low resistance and is used to load the generator, thus providing a braking action. With this type of resistor the shock to the generator is reduced while the shock to the system is increased.

It has been shown[18] that the current limiting type of resistor causes greater phase to ground voltages than a reactance would for the same gain in stability. Further, the reactor is usually cheaper. Therefore as a current limiting device reactors are in general preferable. Whether or not a braking type of resistor is preferable to a current limiting reactor is a question which is not yet entirely clear. However, for general applications the reactor appears preferable since the choice of braking resistor requires very careful study in each particular case, which is not the case with reactors. Furthermore with a braking resistor there is a greater danger of telephone interference than if either a current limiting resistor or reactor is used.

(*d*) *Synchronous Condensers*

The authors believe that the use of synchronous condensers wholly or principally as an aid to stability is not in general desirable, except perhaps in a few isolated cases. This belief is based on the observation of certain synchronous condensers under transient conditions and also on calculations of the type leading to curves shown in Figs. 24 and 25. These curves show how slight is the gain obtained in the case for which the calculations were made. Thus it appears that normally condensers should only be purchased on the basis of their function in supplying wattless kv-a. In other words, it is thought that in most cases the gain is not sufficient to justify them solely on the basis of their stabilizing effect. In cases where it is desired to in-

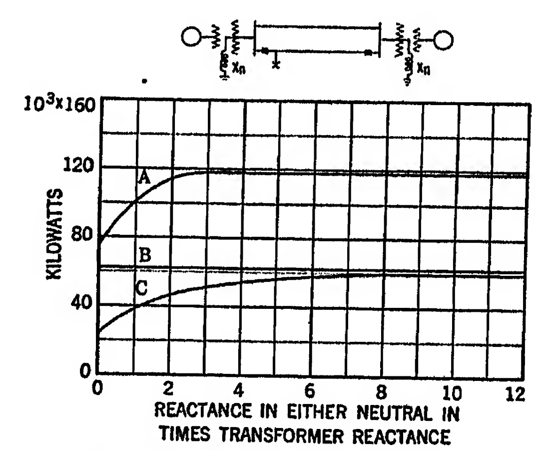


FIG. 6—POWER WHICH MAY BE CARRIED THROUGH FAULTS OUTSIDE THE GENERATOR TRANSFORMERS *Versus* REACTANCE IN EITHER NEUTRAL WHEN THE FAULT IS CLEARED IN 1.0 SEC.

Long lines with high-voltage busses and no mid-bus
A One conductor-to-ground fault
B Conductor-to-conductor fault
C Two conductor-to-ground fault

crease any stabilizing effect which they may accomplish this may be done advantageously by providing a balancing type of regulator and high ceiling exciters. When considering the use of condensers it is important to bear in mind that they may not and apparently usually do not increase the transient limit as much as the steady state limit.

(*e*) *Governors*

From a stability standpoint governors should operate quickly and should possess anti-hunting features tending to reduce swinging after disturbances. Governor operation in direct response to fault indication may prove desirable. Field tests as an aid in improvement of governor characteristics under transient conditions would be very desirable.

Automatic control of frequency is being tried on certain systems. To the extent that each system and each station hold very closely to the exact system frequency, the problem of tie-line loading should be simplified and a corresponding improvement in stability will result.

(*f*) *Transformers*

Present indications are that power transformer neutrals should be insulated sufficiently to permit the use of neutral reactors. The value of neutral reactance which satisfies the requirements previously mentioned

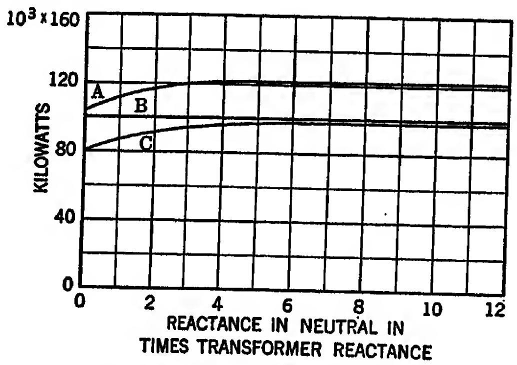


FIG. 7—POWER WHICH MAY BE CARRIED THROUGH FAULTS OUTSIDE THE GENERATOR TRANSFORMERS *Versus* REACTANCE IN THE NEUTRAL WHEN THE FAULT IS CLEARED IN 0.2 SEC.
Long lines with a high-tension bus and no mid bus. For diagrams see Fig. 6
A 1 conductor to ground fault
B Conductor to conductor fault
C 2 conductor to ground fault

generally does not give rise to neutral voltages requiring full insulation. Therefore at the higher voltages, economic considerations seem to justify the building of transformers with lowered neutral insulation. For example, up to the present, 220-kv. transformers have been designed with 73-kv. insulation at the neutral.

The use of double winding transformers appears to be an interesting possibility. In general a higher transformer reactance decreases the fault current and the shock to the generators and system, during the time the fault is on. On the other hand, when the faulty line is cleared, the synchronizing power between generator and system is reduced. The synchronizing power before the fault is also reduced resulting in a greater initial angle between the generator and system linkages behind transient reactance.

With a high-voltage bus arrangement there results a definite advantage in favor of low transformer reactance, from the standpoint of stability. On the other hand with a low voltage bus and split bus discussed later this advantage is less prominent and in fact a high reactance may be found advantageous in these cases. The question of the possible desirability of specifying low transformer reactance involves not only relative transformer costs and the effect on system stability but also the problem of increased circuit breaker duty. This question has not as yet been definitely evaluated and should be given further study.

(*g*) *Lightning Arresters*

The primary function of lightning arresters is to reduce the overvoltage surges to such values that they will not damage terminal apparatus and since their effect is relatively local the reduction in number of line outages attributable to lightning arresters placed only at the ends of the line is not great.

In two instances, lightning arresters have been installed at frequent intervals along the transmission line to prevent the flashover of insulators by lightning, with favorable results.

(*h*) *Loading Resistors*

It has been proposed* to load the generators upon occurrence of a fault by suddenly closing a low-tension switch connecting a three-phase resistor across the generator terminals. The switch would remain closed for a short time, say one-half second, and then open automatically. This would have the effect of reducing the shock to the generator during the time when the fault was on. By opening the switch at an appropriate time a considerable gain in power limit should be obtained in most cases.

(*i*) *Series Capacitors*

The use of series capacitors has been considered as a means for correcting for line reactance. As at

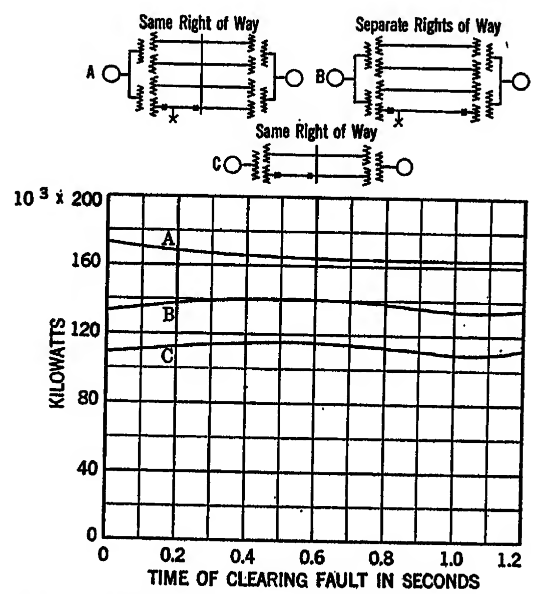


FIG. 8—POWER WHICH MAY BE CARRIED THROUGH ONE CONDUCTOR TO GROUND FAULT OUTSIDE GENERATOR TRANSFORMERS *Versus* SWITCHING TIME

present designed, capacitors are equipped with protective spark gaps and short circuiting switches in order to avoid excessive voltages during short circuit. On this account their value for transient stability would at first appear questionable. It may be shown, however, that this feature can be turned to advantage when a low voltage bus is used at either end of the line, provided the condensers are large enough so that the

*This device was suggested by one of our associates, Mr. W. F. Skeats.

protective gap can be so adjusted that a fault on one line does not short out the capacitors on the remaining line. In this case the capacitors on the affected line short out on the occurrence of a fault and thus increase the total reactance to the fault. The unaffected lines will retain their low reactance. This proposal has great promise but economic considerations will usually prevent its adoption at the present time.

(j) *Switches and Relays*

When the duration of short circuit is low, the impulse given to machine rotors is small, and hence stability is

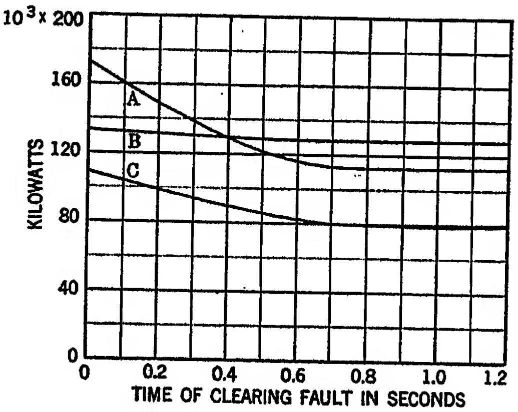


Fig. 9—Power which may be Carried through a Two Conductor to Ground Fault Outside Generator Transformer

For conditions see diagrams *A*, *B*, and *C*. Fig. 8

improved. From this standpoint, therefore, high speed in both relays and circuit breakers is very desirable.

TABLE I

Time of clearing fault in seconds	Power which may be carried through a two-conductor-to-ground fault
0.0	100 per cent
0.1	83 per cent
0.2	68 per cent
0.3	56 per cent
0.5	42 per cent
0.75	33 per cent

Table I shows the average reduction in power limit over transmission systems involving waterwheel generating capacity due to delayed switching,* with power limit at zero switching time as reference, for two-conductor-to-ground faults.

Lines

(a) *Over Insulation of Lines*

The tendency has been to increase the insulation on lines. For example, the 220-kv. lines of the Southern California Edison Co. were insulated originally with 11 disks. Later, when the 220-kv. lines were built for the Philadelphia Electric Co. Conowingo development, 14 disks were used and lines are now being planned involving the use of 18 disks. It appears that by the use of a suitable number of disks, it should be possible to eliminate arc-overs due to voltages induced by near-by strokes of lightning, but even with ground wires, the possibility of entirely eliminating arc-overs due to direct strokes is questionable.

*For high voltage bus arrangement.

(b) *Ground Wires*

The beneficial effect of ground wires[3] is to lower the voltage induced by lightning in the vicinity. They also are thought to lower the probability of direct strokes on the line wire, but not necessarily to prevent their occurrence. Ground wires are also beneficial in that they attenuate the traveling waves which result from lightning or other causes. Low resistance ground wires lower the zero phase sequence impedance and thus make one-conductor and two-conductor-to-ground faults more severe if sufficient neutral impedance is not used. In addition, the tower footing resistance is equalized and results in a more uniform ground current for relaying. Excessive potential gradients at the tower footings are also reduced by distributing the ground current through several towers.

(c) *Horizontal versus Vertical Spacing*

With horizontal spacing there generally results a lower total number of faults due to lightning than with

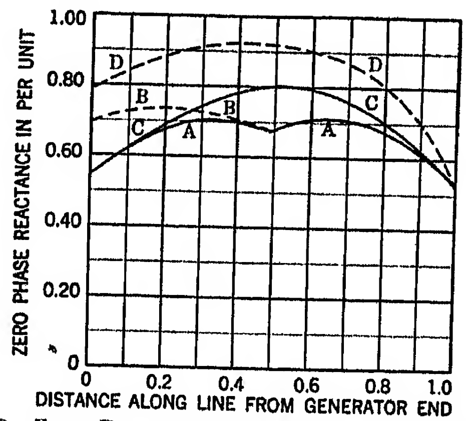


Fig. 10—Zero Phase Sequence Reactance Viewed from the Point of Fault versus Position of Fault for Systems shown in Diagrams A, B, C, and D. Fig. 4

Calculations based on

A-A High-tension bus and mid bus
B-B High-tension bus and no mid bus
C-C Low-tension bus and mid bus
D-D Low-tension bus and no mid bus
Note: *D-D* becomes *A-A* at mid bus

vertical spacing. On the other hand, with horizontal spacing most of the faults appear to involve two conductors and ground while with vertical spacing most of the faults involve only one conductor and ground. There is some question as to which of these arrangements results in the lower number of the more severe two-conductor-to-ground type of fault. Field data would be of value in this connection.

(d) *Power Arc Suppression Devices*

The use of Petersen coils and lightning arresters in this connection has already been referred to above.

The extinction of the power arc following an insulator flashover by means of a fuse at the insulator, rather than by tripping the line, has been tried with some success.

System Connections

*(a) High-Voltage Bus**

The use of a high-tension bus either at the generator or system end of the line or as a mid bus results in a maximum shock during the occurrence of a fault, but a minimum reduction in synchronizing power after the faulted line has been cleared. If the shock is already

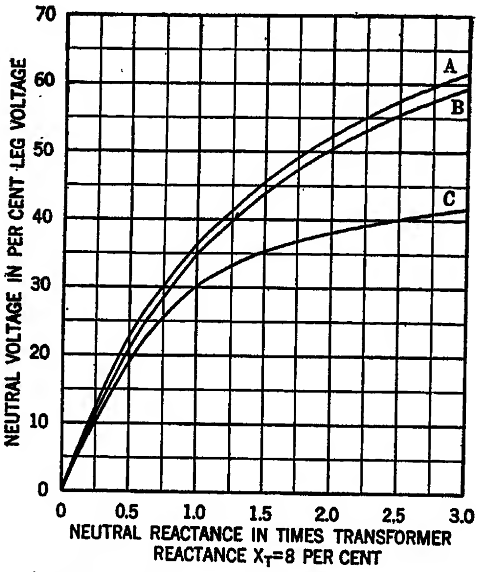


Fig. 11—Curves showing Neutral Voltages under Ground Fault Conditions versus Reactance in Neutral

A Neutral voltage with one conductor to ground fault on the high-tension bus at the system end *versus* neutral reactance of system end; neutral reactance of generator end $= 3\ X_T$

B Same as *A* except neutral reactance of system end $= 2\ X_T$

C Same as *B* except two conductor to ground fault

small as in the case of a single conductor to ground fault when neutral reactances are employed, or if the duration of the fault is short as when high-speed switches are used, this is a desirable arrangement from a stability standpoint. If these conditions do not exist this type of arrangement may prove unsatisfactory.

*(b) Low-Voltage Bus**

A low-tension bus has the advantage over a high-tension bus that the reactance to the fault is increased. On the other hand, when the fault clears the synchronizing power is less than with a high-voltage bus. If there are several lines, say four or more, the low-voltage bus is very advantageous. A further advantage is that high speed switching is not required, provided the faults do not involve more than one conductor.

For long distance transmission this arrangement will usually be uneconomical, but for transmission over relatively short distances it offers great promise. The curves in Fig. 2 show the indicated results with this arrangement.

*Figs. 4 and 5 show the comparison between high- and low-voltage buses.

(c) Split Bus

Another solution is to use a low-voltage bus at the system end of the line and to split the lines at the generator end, putting part of the generating capacity on each bus.[5, 6, 7] When this is done it is usually possible for the generators on any one line to ride through the disturbance occasioned by a fault on another. However, for long distance transmission lines even with this arrangement a higher speed of switching than has heretofore been commonly available in the higher voltage switches will be required to insure stability.

It seems possible that high transformer reactance at the system end of the line may be beneficial with this arrangement since it tends to reduce the shock to the generators on the unaffected lines. This point is being investigated.

Conclusion

One outstanding conclusion which may be derived from the foregoing discussion is that the development of high-speed high-tension circuit breakers and relays will mark the greatest single advance in the solution of present stability problems.

Part II

SIMPLIFIED METHODS OF CALCULATION

Ideal Case of Two Machines

This case neglects governors, damping, decrements, and resistance and has been thoroughly discussed in a

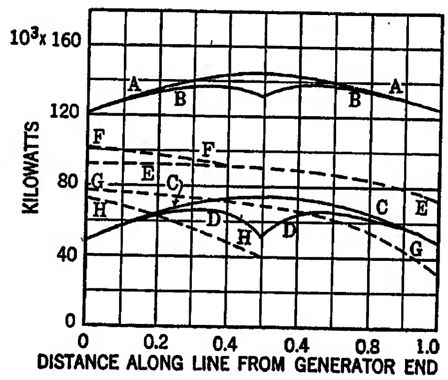


Fig. 12—Power which may be Carried through a Fault with one Second Switching time

A–A	1 C G fault, no mid bus	High-tension switching
B–B	1 C G fault, mid bus	High-tension switching
C–C	2 C G fault, no mid bus	High-tension switching
D–D	2 C G fault, mid bus	High-tension switching
E–E	1 C G fault, no mid bus	Inst. low-tension switching
F–F	1 C G fault, mid bus	Inst. low-tension switching
G–G	2 C G fault, no mid bus	Inst. low-tension switching
H–H	2 C G fault, no mid bus	Inst. low-tension switching

Note: *F–F* and *H–H* extend only to mid bus, with fault beyond this point, the low-tension switches at generator end are unable to discriminate

previous paper.[1] Appendix VIII of the present paper supplements the previous paper by the addition of more extensive charts for the determination of angular position at any instant after a disturbance and of charts to facilitate the calculation of power limit with quick switching.

The new angle-time curves were obtained on the Integraph at Massachusetts Institute of Technology.

Ideal Case of Two Machines Including the Effect of Resistance

Methods which previously were confined to the solution of ideal cases have been extended to apply to circuits with resistance. This case is discussed in Appendix II.

General Case of Two Machines

This case considers the factors neglected in the ideal case. The method of calculation has been discussed before.[1]

More than Two Machines

The general method of calculation is discussed in general in the same paper referred to above. A specific

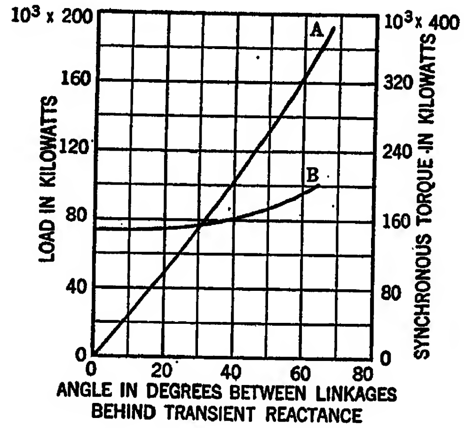


Fig. 13—Auxiliary Curves used in the Transient Stability Investigation of the System shown in Fig. 4

A Load on 120,000-kv-a. generating station *versus* angle between linkages behind transient reactances

B Maximum torque which would be exerted by excitations corresponding to the steady-state angle of the linkages behind transient reactance

example involving three machines is explained and treated in greater detail in Appendix IV.

Circuit Diagrams

There are in general four diagrams which are required to permit the full calculation of stability according to present methods. There are:

Synchronous positive phase sequence impedance diagram.

Transient positive phase sequence impedance diagram.

Negative phase sequence impedance diagram.

Zero phase sequence impedance diagram.

The construction of these diagrams is thoroughly described in previous articles.[1, 19] It is important to note that separate diagrams must be made for transient and synchronous impedance even though these are both positive phase sequence impedances. The synchronous impedance can be used in conjunction with the negative and zero phase sequence impedances in a steady state analysis. In a transient analysis the transient positive phase sequence impedance replaces the synchronous, and is also used in conjunction with the negative and zero phase sequence impedances during unbalanced conditions.

Equivalent Impedance of Open Lines

If one circuit of a three-phase line, connecting two balanced three-phase systems or parts of one system, is opened, the effect is to decrease the positive phase sequence currents. It may be shown that the effect on the positive phase sequence diagram is the same as the insertion of a balanced three-phase impedance equal to the paralleled value of the zero and negative impedances which would be met by a series voltage of the corresponding phase sequence inserted at the point where the circuit is interrupted. Were two lines opened the equivalent series impedance to be inserted would be the series value of the negative and zero phase sequence impedances.

For example, if one phase of one circuit were opened in Fig. 14A the effect from the standpoint of the positive phase sequence impedance would be as shown in Fig. 14B. The negative and zero phase sequence impedance diagrams as met by a series voltage at the point of fault are shown in Figs. 14C and 14D.

In case resistance is considered the same procedure would apply.

Equivalent Impedance of Fault

It has been shown[1, 23] that single-phase faults may be represented by the equivalent three-phase fault of the appropriate kind. In Fig. 15 is shown the equivalent fault impedance for the three common faults which are liable to occur on a system.

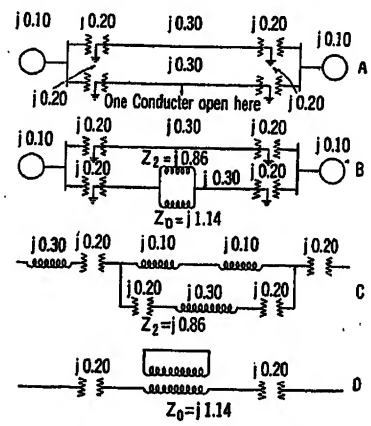


Fig. 14—Equivalent positive Phase Sequence Impedance Diagrams for a Circuit with One Conductor Open

Note: Zero phase sequence impedance of one line assumed equal to three times the positive; the mutual between two lines assumed one-half of this

These results can be obtained from the preceding by regarding a one-conductor-to-ground fault as a three-phase fault with two conductors open, a line-to-line fault as a three-phase fault with one conductor open and no neutral connection, and a two-conductor-to-ground fault as a three-phase fault with one conductor open.

Choice of Equivalent Machine to Represent a System

Ordinarily a system, if closely linked together, will be represented by a single machine. The four impedances of this machine should be determined

separately on the calculating table using the four corresponding equivalent circuits representing the system, mentioned above.

The inertia constant of the equivalent machine is the sum of the inertia constants of all the machines in the system expressed in terms of a common base power.

When the resistances involved are not too large the d-c. calculating table may be used to advantage in obtaining the reactances of the equivalent machine. This method is discussed in detail in an article by Mr. A. P. Mackerras.[19] In case the resistance is appreciable an a-c. calculating table is essential.

Zero Phase Sequence Reactances

The zero phase sequence reactance diagram is often more difficult to evaluate because of mutual reactances between lines and between windings in transformers and generators. Special attention has been given to this and formulas are presented in Appendices IV and V.

Essential Data for a Stability Study

It is considered essential to have the following information submitted, before attempting to make a stability study on a power system.

(a) A single line *circuit diagram* of the system under consideration as well as of adjacent systems which may be connected, giving
 1. Location of, and
 2. Electrical arrangement of
  (I) Lines
  (II) Generators
  (III) Transformers
  (IV) Reactors
  (V) Loads
  (VI) Grounds

Accompanying such a circuit diagram, it is desirable to have data tabulated as accurately as possible under the following subjects.

(b) Lines
 1. Voltage
 2. No. circuits
 3. Length
 4. Conductor size
 5. Number of ground wires and material

(c) Synchronous Machines
 1. Type
  (I) Turbo generators
  (II) Waterwheel generators
  (III) Frequency sets
  (IV) Condensers
 2. Kv-a. capacity of each
 3. Rev. per min.
 4. Short circuit ratio
 5. Type of excitation
  (I) Self excited
  (II) Separately excited
  (III) Main field rheostat
 6. Type of regulator

(d) Transformers
 1. Type
  (I) Two-windings tep-up
  (II) Three-winding transformers
  (III) Auto transformers
  (IV) Y-Y; Y-Delta, etc.
 2. Kv-a. capacity of each
 3. Reactances
 4. Ground points
 5. Neutral impedances

(e) Loads
 1. Kilowatts from each bus
 2. Power factor
 3. Per cent resistance, induction, and synchronous connected load.

NOTE: Care should be taken to indicate specifically the location and magnitude of future expansions and whether the study is desired for present or future conditions.

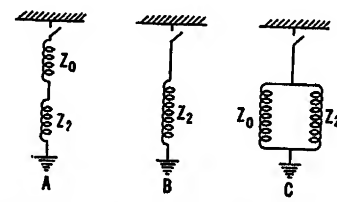


FIG. 15—EQUIVALENT POSITIVE PHASE-SEQUENCE IMPEDANCE DIAGRAMS FOR FAULT CONDITIONS

A Single conductor to ground
B Conductor to conductor
C Two conductor to ground

Acknowledgment

The authors gratefully wish to acknowledge the contributions to this article by Mr. R. H. Park. They also wish to thank Miss Edith Clarke and Messrs. E. M. Hunter and Myron Zucker for their assistance in the preparation of the paper.

Appendix I

Specific Example

An endeavor has been made to investigate the effects of various bus and apparatus arrangements in a typical transmission system which is required to withstand shocks ensuing from major switching operations and fault conditions.

In Fig. 16 is shown the simplified diagram of such a typical generating station delivering power over high-voltage transmission lines to a large interconnected system which is represented as an equivalent motor. The generating station is assumed to consist entirely of waterwheel generators. The power is to be transmitted over 154-kv. lines. where two circuits are considered and over 110-kv. lines where four circuits are considered. These ratios of voltages and number of circuits are chosen in order that the maximum steady state powers under normal conditions may be equal. The curves in Part I show the results found in this particular study.

Constants of the Systems. The generating capacity is assumed to be 120,000 kv-a. and this value is used as

a kv-a. base throughout. Reactances are given in per unit, and inertia constants in seconds. The synchronous, transient, and negative reactances of the generators are assumed to be 0.48,* 0.24, and 0.23 per unit respectively; and the inertia constant, 7.5 seconds. The corresponding constants for the equivalent motor at the receiving end are 0.14 and 0.115 per unit reactance and 105 seconds. The step-up transformers at the generator end have a reactance of 0.08 per unit and the step-down transformers at the receiving end a reactance of 0.10 per unit. The 154-kv. circuits have a reactance of 0.52 per unit each and the 110-kv. circuits 1.04 per unit each. These values are sufficiently large to correspond to long distance transmission and where short lines are considered these values are reduced to 0.19 and 0.38 respectively.

The transformer neutrals at the generator and receiving end have 0.22 and 0.20 per unit reactance respectively which values become 0.66 and 0.60 per unit reactance in the single line zero phase sequence reactance diagram. These values of neutral reactance reduce the severity of ground faults without causing excessive neutral voltages and at the same time allow sufficient ground current to flow for relaying purposes; they are maintained throughout the investigation unless otherwise specified. Fig. 10 gives the zero phase sequence reactance of the system viewed from the point of fault, including lines, transformers, and transformer neutral reactances as a function of the position of fault for two typical bus arrangements. These values were obtained from formulas given in Appendix V -(b)

Assumptions and Methods of Calculation

The following assumptions are made to simplify and expedite the calculations.

(a) Resistance and capacitance are neglected.
(b) Reactances in the direct and quadrature axes are assumed to be alike.
(c) Normal voltage is maintained under steady state conditions on the high-tension side of transformers at the generator end.
(d) The power factor at this point is normally 0.98 lag.
(e) Linkages behind transient reactance of the generator and motor remain constant during the first swing.
(f) No damping torques are considered.
(g) Results are based on the first swing only.
(h) Faults are considered only on the high-tension side of the transformers at the generator end unless otherwise specified.
(i) Constant shaft torque, governor action, and load speed characteristics, neglected.
(j) With one exception, the two breakers necessary to clear the fault, whether high tension or low tension, operate simultaneously.

*Allowing for saturation.

The breakers which must open to clear the fault are shown in black on the respective diagrams. The exception referred to is seen in diagrams *B* and *D* (Fig. 4), where the low tension breakers are assumed to open instantly on the occurrence of a fault. The fault was finally cleared in this case by the opening of the high-tension breaker marked black. The time of this breaker operation is the independent variable in this case.

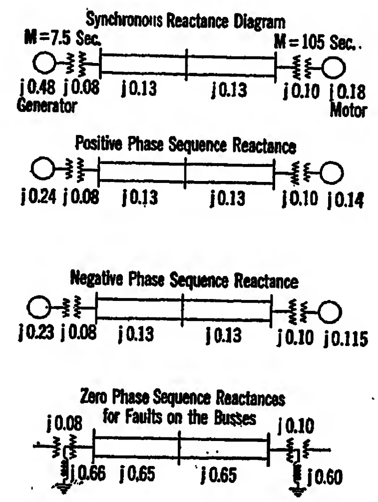


FIG. 16—DIAGRAM SHOWING DISTRIBUTION OF REACTANCES IN A SAMPLE SYSTEM WHICH HAS BEEN USED TO DEMONSTRATE THE EFFECT OF BUS ARRANGEMENTS. WHEN LOW-TENSION BUS ARRANGEMENTS ARE CONSIDERED, THE REACTANCES ARE SIMILAR

Reactance base 120,000 kv-a., 154 kv.
Generator capacity 120,000 kv-a.

Brief Review of Methods of Calculations. In order to determine the power which may be transferred through a fault condition with zero switching time two constants only are necessary, *viz.*, the transfer reactance under normal conditions and the transfer reactance when the fault has been cleared. From the ratio of these two reactances the initial angle at which the machines can operate with stability, is determined. Curve *A*, Fig. 13, gives the load on the generator as a function of the initial angle and Curve *B* gives the maximum torque which would be exerted as a function of the initial angle.

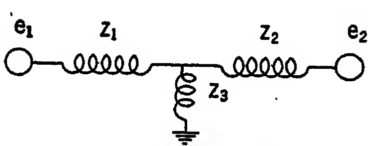


FIG. 17—POSITIVE PHASE-SEQUENCE DIAGRAM USED IN DEMONSTRATING PRINCIPLE OF SUPERPOSITION IN APPENDIX III

In a similar way the power which may be carried through the first swing of the machines, with a fault which remains on the system, is obtained from the ratio of the transfer reactance under normal conditions to the transfer reactance with the fault on. From this ratio the initial angle of the machines for stable operation is determined and the corresponding load is found from

Curve *A*, Fig. 13. These two values give two points on curves showing power which may be passed through a fault *versus* switching time. Generally no gain is obtained with switching times of 0.75 second or 1.0 second.

Intermediate points on the curves are obtained by assuming an initial load and finding the angle at which the fault must be cleared to give stability. To find this angle it is necessary to know three transfer impedances: before the fault occurs, with the fault on, and with the fault cleared. Knowing this angle, time is obtained either by direct calculation if the travel along this

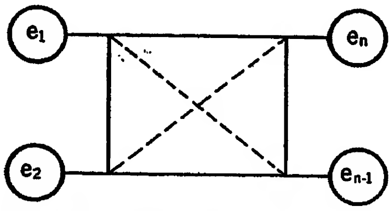


FIG. 18—DIAGRAM SHOWING A REPRESENTATIVE NETWORK

curve is relatively small, or from curves, (see Appendix VIII).

DISCUSSION OF CURVES

(a) The interesting feature shown in the curves of Fig. 2 is that for switching times of the order of 0.75 second, multiple circuit lines with low-tension buses show a decided gain over two circuit lines with high-tension buses. If high-tension buses are used, however, switching times of 0.1 second or less must be obtained to produce stability comparable with that obtained using low-tension buses.

A slight additional advantage would be shown for multiple circuit lines were the transformer capacity per circuit increased by one-third, so as to allow full load to be transmitted over three circuits.

Referring to Fig. 3 it is seen that full load of 120,000 kw. may be transmitted over a long line with high-tension buses and fault duration of 0.75 second with a conductor-to-ground fault. Multiple circuit lines with low-tension buses give a margin of 20 per cent above this and a still greater gain is shown when short lines are considered.

It would thus seem desirable to employ multiple circuit lines with low-voltage buses where the transmission distance is sufficiently short to justify their use economically.

(b) Fig. 4 shows that with fault durations of 0.75 second or greater only 50,000 kw. can be carried through a two-conductor-to-ground fault with high-tension buses throughout. Introducing low-tension buses at one end gives an increase over this of approximately 50 per cent. For fault durations as long as this a mid bus shows no advantage. However, as the fault duration is decreased a mid bus shows an increasing gain because only half a line is switched out to clear the fault. Finally, for very fast switching, a high-tension bus with a mid bus is desirable. This is because the fault is not left on the system long enough to cause much disturbance and when it is cleared, all the transformer capacity is operative and only one section of line is out. Similar curves are shown in Fig. 5 for a single-conductor-to-ground fault. These show a margin of 10 per cent in favor of a mid bus with a low tension bus arrangement at one end.

The effect of a low tension bus at the system end was not investigated. However, it is evident that with only two circuits the use of high-speed switches together with high-voltage buses is essential if a power limit approaching the full generator capacity is desired.

(c) In Fig. 6 it is seen that only relatively small amounts of power can be passed over a solidly grounded system under either a two-conductor-to-ground or one-conductor-to-ground fault condition with fault durations of 1.0 second. If reactance is added to the neutrals an appreciable gain is obtained. When 3 times the transformer reactance has been added to either neutral the increase in power for a two-conductor-to-ground fault is 70 per cent (for a single-conductor-to-ground fault practically 100 per cent) of the gain which could be obtained by completely isolating the neutrals.

Somewhere between two and three times transformer reactance seems to be the desirable limit of neutral reactance, considering telephone interference problems, relaying, and neutral voltages. These values give practically all the gain for stability purposes that would be obtained by isolating the neutrals.

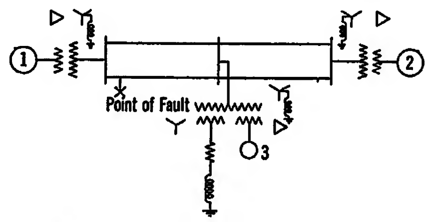


FIG. 19—SYSTEM SET-UP FROM WHICH SWING CURVE ON FIG. 24 WAS CALCULATED
For impedance see Fig. 20

With three times the transformer reactance in the neutrals and 1.0 second switching time, only 50,000 kw. can be carried through a double-conductor-to-ground and 62,000 kw. through a single-conductor-to-ground fault. From Fig. 7 these values are increased to 94,000 and 100,000 when the fault duration is reduced to 0.2 second. These are gains of 47 and 38 per cent, respectively. The gain due to fast switching is even greater with solid neutrals.

(d) Fig. 1 shows that for 1.0 second switching a slight gain is indicated when the generator transient reactance is reduced.

(e) Fig. 11 shows the increase in neutral voltages during ground fault conditions, as the neutral reactance is increased. Curve *C* is for a two-conductor-to-ground fault and it is seen that the neutral voltage is less in this case than for a single-conductor-to-ground fault. This will always be the case if $\mathbf{Z}_2 \gtrless \sqrt{\mathbf{Z}_1 \mathbf{Z}_0}$ at

the fault; a condition which usually obtains. The subscripts refer respectively to negative, positive, and zero phase sequence.

Approximately 60 per cent normal leg voltage is obtained with three times the transformer reactance in the neutrals in this example.

In the investigation of multiple circuit lines it is well to bear in mind that building each line on a separate right of way would substantially decrease the probability of simultaneous outage of two circuits due to lightning disturbances. If neutral reactors were not employed this isolation of circuits would increase the

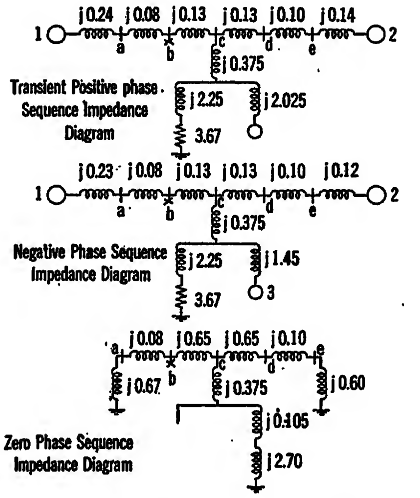


FIG. 20—EQUIVALENT IMPEDANCE DIAGRAMS FOR THE SYSTEM SHOWN ON FIG. 19 WITHOUT FAULT

severity of faults near buses since the zero phase sequence reactance is less.

Throughout this discussion the beneficial effect of high-speed switching has been more and more apparent. The curves all tell the same story, namely that one of the largest items affecting improvement in system stability is probably the introduction of high-speed, high-tension circuit breakers with high-speed relays.

Appendix II

EQUAL AREA METHOD OF CALCULATING STABILITY WHEN RESISTANCE IS INVOLVED

The equal area method has been extensively used for calculating the stability of a generator feeding a synchronous load over a line of negligible resistance.[1]

However, the same general method may be used when line resistance is included, and when there is impedance as well as synchronous load.

Specifically, the driving point and transfer impedances are found as explained in Appendix III. This method supplants the methods previously used where the impedances of the load at each end of the line were combined with that of the machines.

The torque angle curves for each equivalent machine may then be found. (For salient pole machines, formulas (52) and (25) of Doherty and Nickle's *Synchronous Machines II* are available.)

The differential equations of motion are

$$M_1' \, p^2 \, \delta_1 = f_1 \, (\delta_1 - \delta_2) \tag{1}$$

$$M_2' \, p^2 \, \delta_2 = f_2 \, (\delta_1 - \delta_2) \tag{2}$$

where

M_1 = inertia constant of machine 1 in seconds

$M_1' = \dfrac{M_1}{2 \pi f}$ and f = normal frequency.

$f_1 (\delta_1 - \delta_2)$ = synchronizing power of machine 1

also

M_2' and $f_2 (\delta_1 - \delta_2)$ are similar quantities for machine 2.

Then there is

$$p^2 \, \delta = \frac{f_1 \, (\delta)}{M_1'} - \frac{f_2 \, (\delta)}{M_2'} \tag{3}$$

where

$$\delta = \delta_1 - \delta_2$$

$$p = \frac{d}{d\,t}$$

That is, the acceleration of δ is proportional to

$$\frac{f_1 \, (\delta)}{M_1'} - \frac{f_2 \, (\delta)}{M_2'} \tag{4}$$

consequently, the rate of change of δ will be zero if

$$\int_{\delta_0}^{\delta} \left[\frac{f_1 \, (u)}{M_1'} - \frac{f_2 \, (u)}{M_2'} \right] d\,u = 0 \tag{5}$$

which is the equal area criterion of stability that is sought and was derived by Mr. R. H. Park. This

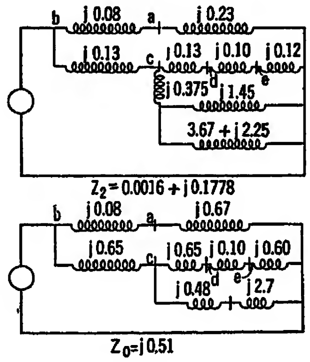


FIG. 21—NEGATIVE AND ZERO PHASE-SEQUENCE IMPEDANCE DIAGRAMS AS VIEWED FROM POINT OF FAULT SHOWN ON FIG. 19 ASSUMING A TWO-CONDUCTOR TO GROUND FAULT, THE THREE-PHASE FAULT

$$\text{Impedance is } Z_F = \frac{Z_0 \, Z_2}{Z_0 + Z_2} = 0.0010 + j\,0.1318$$

method is general and may be employed to determine stability either when the fault remains on indefinitely or when it is cleared at some definite time. If switching is involved the functions f_1 and f_2 will of course change discontinuously during the process of integration.

In the following a detailed formula is developed*

*This formula was developed by Mr. M. Zucker.

which applies to the particular case of two synchronous machines with either long delayed or instantaneous switching. The equal area criterion that has been established is equivalent to the statement that the machines have come to rest with respect to each other before the acceleration becomes finally zero. In order to find δ_f (the angle for zero acceleration) we have, referring to Appendix III and to Appendix IV, paragraphs 6 and 7 for definition of terms.

$$\frac{T_1 - T_{11} - K_{12}\sin(\delta_f - \alpha)}{M_1'} = \frac{T_2 - T_{22} + K_{12}\sin(\delta_f + \alpha)}{M_2'} \qquad (6)$$

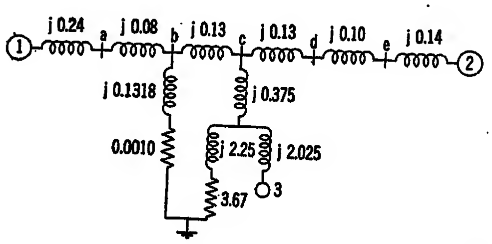


FIG. 22—EQUIVALENT POSITIVE PHASE-SEQUENCE IMPEDANCE NETWORK FOR SYSTEM SHOWN ON FIG. 19 WITH TWO-CONDUCTOR-TO-GROUND FAULT

where

T_1 is torque acting on generator from prime mover

T_2 is torque acting on motor from load (this is a negative quantity unless motor is acting as a generator).

Let $$\frac{M_2'}{M_1'} = R$$

This reduces to

$$\frac{R(T_1 - T_{11}) - T_2 + T_{22}}{K_{12}} = (R+1)(\cos\alpha\sin\delta_f) - (R-1)(\sin\alpha\cos\delta_f) \qquad (7)$$

Let $(R-1)\sin\alpha = m$

$(R+1)\cos\alpha = n$

$$\frac{R(T_1 - T_{11}) + T_{22} - T_2}{K_{12}} = F$$

Then $$F = n\sin\delta_f - m\cos\delta_f \qquad (8)$$

which can be solved as

$$\sin\delta_f = \frac{nF + m\sqrt{m^2 + n^2 - F^2}}{m^2 + n^2} \qquad (9)$$

This determines the limiting angle. The area sought is

$$A = \frac{1}{M_1'}\int_{\delta_0}^{\delta_f}\left[T_1 - T_{11} - K_{12}\sin(\delta - \alpha)\right]d\delta - \frac{1}{M_2'}\int_{\delta_0}^{\delta_f}\left[T_2 - T_{22} + K_{12}\sin(\delta + \alpha)\right]d\delta \qquad (10)$$

which becomes

$$\frac{M_2'}{K_{12}}A = \frac{\pi F}{180}(\delta_f - \delta_o) + m(\sin\delta_f - \sin\delta_o) + n(\cos\delta_f - \cos\delta_o) \qquad (11)$$

when angles are expressed in degrees.

Thus the criterion for stability is that

$$\frac{\pi F}{180}(\delta_f - \delta_o) + m(\sin\delta_f - \sin\delta_o) + n(\cos\delta_f - \cos\delta_o) \lesseqgtr 0 \qquad (12)$$

Appendix III

POWER FLOW IN A NETWORK HAVING ANY NUMBER OF BRANCHES AND VOLTAGES

The equations for power flow in a network (Fig. 18) have been given before[23] but will be given here in slightly different form for convenience of reference and to define certain terms used in this paper.

Let P_{1E} be the power out of branch 1 and

$\mathbf{I}_1$ be the summation of all currents out of branch 1.

$$P_{1E} = \mathbf{e}_1 \cdot \mathbf{I}_1 \text{ or} \qquad (13)$$

$$P_{1E} = \mathbf{e}_1 \cdot \mathbf{i}_{11} - \mathbf{e}_1 \cdot \mathbf{i}_{21} - \mathbf{e}_1 \cdot \mathbf{i}_{31} - \ldots\ldots \mathbf{e}_1 \cdot \mathbf{i}_{n1} \qquad (14)$$

where

$\mathbf{i}_{11}$ is current in 1 due to voltage at 1.

$\mathbf{i}_{n1}$ is current in 1 due to voltage at n

$$\mathbf{i}_{11} = \frac{\mathbf{e}_1}{\mathbf{Z}_{11}} \quad \mathbf{i}_{n1} = \frac{\mathbf{e}_n}{\mathbf{Z}_{n1}} \qquad (15)$$

$$P_{1E} = \mathbf{e}_1 \cdot \frac{\mathbf{e}_1}{\mathbf{Z}_{11}} - \mathbf{e}_1 \cdot \frac{\mathbf{e}_2}{\mathbf{Z}_{21}} - \ldots\ldots \mathbf{e}_1 \cdot \frac{\mathbf{e}_n}{\mathbf{Z}_{n1}} \qquad (16)$$

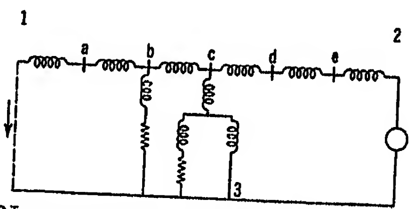


FIG. 23—NETWORK ARRANGEMENT OF FIG. 22, TO MEASURE TRANSFER IMPEDANCE BETWEEN 1 AND 2 AND DRIVING POINT IMPEDANCE AT 2

Going to scalars, since $Z_{1n} = Z_{n1}$ and $\theta_{1n} = \theta_{n1}$

$$P_{1E} = \frac{E_1^2}{Z_{11}}\cos\theta_{11} - \frac{E_1 E_2}{Z_{12}}\cos(\delta_{12} + \theta_{12}) \ldots\ldots\ldots - \frac{E_1 E_n}{Z_{1n}}\cos(\delta_{1n} + \theta_{1n}) \qquad (17)$$

where

θ_{1n} is angle of $\mathbf{Z}_{1n}$

δ_n is angle of $\mathbf{e}_n$

$\delta_{1n} = \delta_1 - \delta_n$

and Z_{11} is the driving point impedance at 1 and Z_{12} is the transfer impedance between 1 and 2

Write $\theta_{1n} = 90° - \alpha_{1n}$

or $\alpha = 90° -$ power factor angle

Then (17) may be rewritten in the alternative form

$$P_{1E} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \ldots\ldots$$

$$\ldots\ldots\ldots + \frac{E_1 E_n}{Z_{1n}} \sin (\delta_{1n} - \alpha_{1n}) \qquad (18)$$

which is often found more convenient

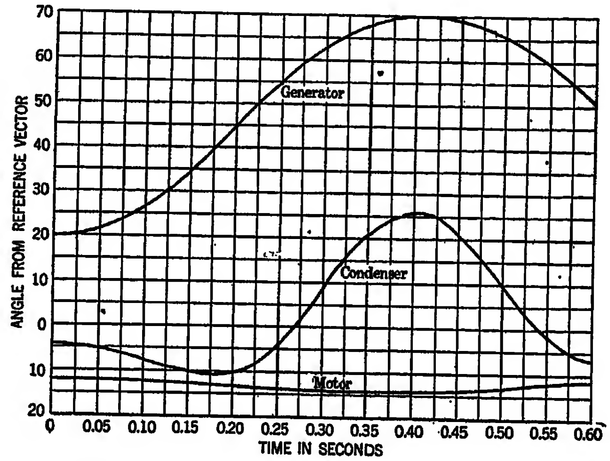


FIG. 24—FLUX LINKAGE ANGLE *Versus* TIME FOR A TWO-CONDUCTOR FAULT AT GENERATOR END OF LINE. RESISTANCE LOAD AND CONDENSER AT MID BUS

Initial generator load = 95,000 kw
Initial motor load = 70,000 kw.
Initial condenser load = 25,000 kv-a.
Initial shunt load = 25,000 kw.

Example:—See Fig. 17

$$P_{1E} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \qquad (19)$$

where

$$\mathbf{Z}_{11} = \mathbf{Z}_1 + \frac{\mathbf{Z}_2\,\mathbf{Z}_3}{\mathbf{Z}_2 + \mathbf{Z}_3}$$

$$\mathbf{Z}_{12} = \frac{\mathbf{Z}_1\,\mathbf{Z}_2 + \mathbf{Z}_1\,\mathbf{Z}_3 + \mathbf{Z}_2\,\mathbf{Z}_3}{\mathbf{Z}_3}$$

Appendix IV

SAMPLE SWING CURVE CALCULATION

Assuming that the original circuit has been resolved into one that properly represents the actual conditions, the steps in calculating a swing curve may be outlined as follows:

1. Draw the positive, negative, and zero-phase sequence impedance diagrams. Fig. 20 shows the component diagrams corresponding to the simplified circuit of Fig. 19.

2. Find the negative and zero-phase sequence driving point impedances at the point of fault and determine the equivalent impedance of the fault. These are illustrated in Fig. 21.

3. Draw the diagram of the system for fault conditions. This is illustrated in Fig. 22 which corresponds to a two-conductor-to-ground fault.

4. From initial load conditions, find the magnitude and phase angle of the vectors representing machine linkages, which are represented by voltages behind transient reactance (Table III gives values for numerical example). In this example unit voltage was held at points b, c, and Fig. 20,—point c being considered the reference vector.

5. Find the "angular acceleration constant"

$$k = \frac{360\, f\, (\Delta\, t)^2}{M} \qquad (20)$$

where

f is normal frequency
$\Delta\, t$ is time interval selected
M is inertia constant

for each machine. A time interval of 1/20 of a second is recommended for most cases. Values for these are shown in the table.

6. Calculate driving point and transfer impedances (only the latter need be found if there is no resistance). Referring to Fig. 23, $\mathbf{Z}_{11}$ is the driving point impedance measuring the voltage at 1 when unit current flows there. $\mathbf{Z}_{12}$ is the transfer impedance measuring the voltage at 1 causing unit current to flow at 2, all other voltages being zero.

7. Find the power as the transient begins, by adding the components for each machine. The driving point power output is

$$P_{11} = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} \qquad (21)$$

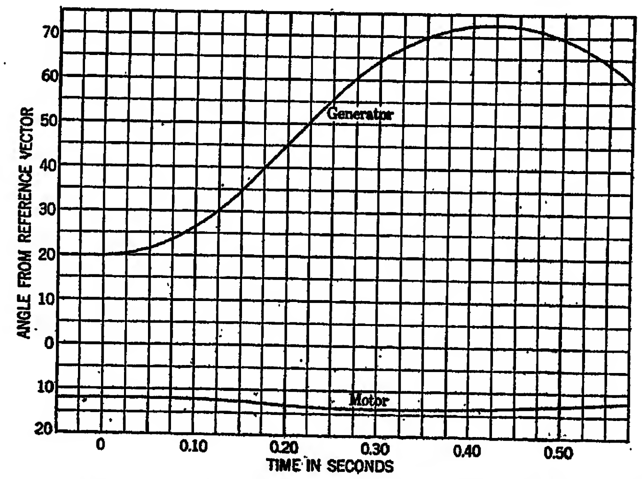


FIG. 25—FLUX LINKAGE ANGLE *Versus* TIME FOR A TWO LINE TO GROUND FAULT AT THE GENERATOR END OF LINE. RESISTANCE LOAD AT MID BUS

Initial generator load = 95,000 kw.
Initial motor load = 70,000 kw.
Initial shunt load = 25,000 kw.

(If there is no resistance this term becomes zero.) The transfer power component indicating power flowing at 1 toward 2 is

$$P_{12} = \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \qquad (22)$$

In case normal regulators are acting we may assume the linkages to remain constant over the period of the swing. Then $\frac{E_1 E_2}{Z_{12}}$ is constant. This assumption is not essential but should be made where justifiable, as it greatly simplifies the calculations. In this case we may define $K_{11} = \frac{E_1^2}{Z_{11}}$, $K_{12} = \frac{E_1 E_2}{Z_{12}}$ etc.

Considered as per unit values it is convenient to note that these expressions for power may be taken as torque by writing T instead of P.

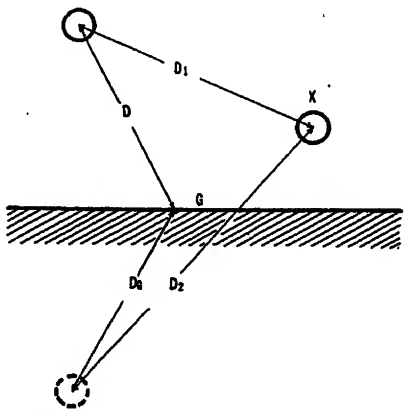


FIG. 26—DIAGRAM FOR ILLUSTRATING THE FORMULA FOR FLUX LINKAGES AT X WITH A TRANSMISSION LINE CONDUCTOR AND ITS ASSUMED IMAGE

8. Find the torque available to accelerate or decelerate each machine by taking the difference between mechanical and electrical torques.

Thus $$T_{a1} = T_1 - (T_{11} + T_{12} + T_{13}) \qquad (23)$$

Where

T_{a1} is net accelerating torque

T_1 is mechanical accelerating torque on machine 1 and in the following example is assumed to remain constant during the swing. It is thus equal to the mechanical accelerating torque just prior to the fault.

9. The change in angle for the first time interval* is then

$$\Delta\,\delta_1 = \frac{k\,T_o}{2}$$

for each machine, where the subscripts from here on, to and including Equation (27), refer to the instant at the end of the successive time intervals instead of to the particular machines. This should result in values of the order of 1 to 2 degrees for the machines that move most. (In the example, for instance, this term is 1.7° for 1 and 1.1° for 3.) If considerably greater values are obtained, it indicates that the time interval chosen is too great.

10. The change in angle for the first period should be added, with due regard to sign, to the initial angle. This gives the angle between machines at the end of the first period. That is

$$\delta_1 = \delta_o + \Delta\,\delta_1$$

11. Repeat the process of finding torques for the second period. Find the change in angle, during the second period as:

$$\Delta\,\delta_2 = \Delta\,\delta_1 + k\,T_1 \qquad (24)$$

Then: $$\delta_2 = \delta_1 + \Delta\,\delta_2 \qquad (25)$$

similarly $$\Delta\,\delta_3 = \Delta\,\delta_2 + k\,T_2 \qquad (26)$$

$$\delta_3 = \delta_2 + \Delta\,\delta_3 \text{ etc.} \qquad (27)$$

Thus, in the example, see Table IV, the angle change at the end of the first interval was 1.7 degrees per interval. The acceleration component during the second period is 3.2, making the total change in angle 4.9 degrees, and bringing the angle of the generator to 26.6 deg. Continue this process for as long as desired or until such time as the assumptions can no longer reasonably hold.

12. If switching or a second transient of any kind occurs, compute the T's under the first transient conditions for the period at which the change occurs (*i. e.*, T_{a1} for 0.2 second would be 0.277 if nothing changed in the example). Then compute the T's for the same period under the new conditions (T_{a1} for 0.2 second would be $-$ 0.274 if the new conditions held throughout the period).

Average them (0.0016) and, using this for the T, proceed as before. The curve has been plotted in Fig. 24. A similar calculation, made for the case with the condenser omitted, led to the curve of Fig. 25.

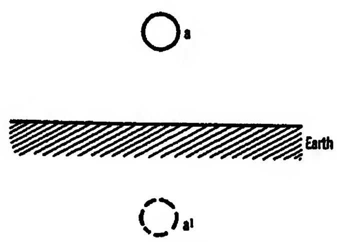


FIG. 27—EQUIVALENT CONDUCTOR ARRANGEMENT OF A SINGLE-CIRCUIT LINE

Appendix V

ZERO PHASE SEQUENCE IMPEDANCE OF LINES WITH CONNECTED APPARATUS

PART A THEORETICAL BASIS

In order to find the zero phase sequence impedance of a transmission line it is strictly necessary to consider the proximity effect of the line and the earth and determine the actual current path throughout the earth. Rüdenberg and Carson have studied this effect. However it is probably greatly variable due to different soil conditions and thus a simplified method is in order.

Two assumptions might be made as limiting conditions. (a) The resistivity is high so that the current

*Appendix XII of Bibliography 1.

penetrates indefinitely depthwise in the earth, and (b) the resistivity is zero so that all the alternating current is confined to an infinitesimally thin lamina at the surface.

Actually conditions are intermediate between these extremes. Thus we may choose case *b* for calculation and empirically revise the answer in the direction of an intermediate value.

In case *b*, the field between the surface and the wire is the same as though the return current flowed in an image conductor having the radius of the line conductor and situated an equal distance below the surface. This follows because no alternating flux can penetrate a perfect conductor. The boundary condition at the surface is that of a flux line everywhere parallel to the surface. This is the same as would be produced by the line conductor with its image, which thus correctly represents the assumed condition. The empirical modification consists in receding the image to a location where the calculations check test, in a specific instance, then using this same image depth in other cases where the soil conditions are thought to be the

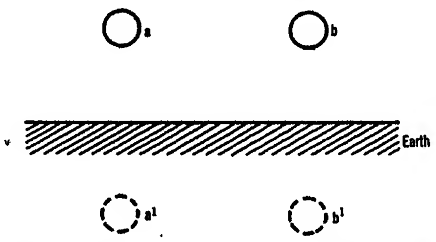


FIG. 28—EQUIVALENT CONDUCTOR ARRANGEMENT OF A DOUBLE-CIRCUIT LINE

same, or where it is desired to calculate the mutual effect of parallel lines.

Thus a simple and approximately correct engineering method is obtained.

In Fig. 26 the linkages per unit length of line* are

$$\Psi = 2\,I \log \frac{D_0}{D_1} - 2\,I \log \frac{D_0}{D_2} = 2\,I \log \frac{D_2}{D_1}$$

*A much more satisfactory way of viewing this problem (though perhaps not so familiar to most engineers) is to identify the linkages per unit length of line with the vector magnetic potential. Thus

$$\Psi = \int \frac{\mathbf{i}\, d\, v}{r}$$

where $\mathbf{i}$ is vector current density
r is distance between Ψ and $\mathbf{i}$
$d\,v$ is a volume element.

This integral need only be taken over the volume of the conductors. By forming it over the volume of a pair of parallel line wires making up a circuit the potential is found at any point, specifically on a neighboring conductor and the formula given above for linkages is obtained. The linkages per unit length are thus related to magnetomotive force by means of the relation

$$\mathbf{H} = \text{Curl}\,\Psi$$

The product of permeability by the time derivative of Ψ thus gives volts per unit length of line induced on the neighboring conductor by the circuit considered, which is the quantity sought.

between x and any point on the ground plane, where
I is current in conductor
D_1, D_2 are geometric mean distances as given in figure.

This involves the assumption that an average Ψ is obtained, thereby neglecting any parasitic currents which may be induced.

A three-phase line with three wires in parallel and transposed so that the current is equal in each (for zero phase sequence calculations) is often considered as a

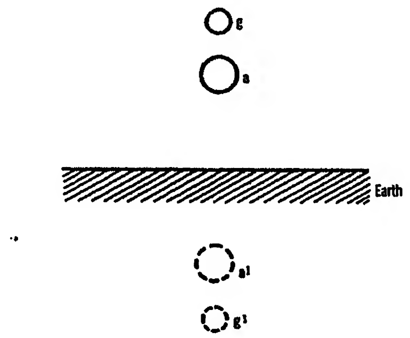


FIG. 29—EQUIVALENT CONDUCTOR ARRANGEMENT OF A SINGLE-CIRCUIT LINE WITH GROUND WIRES

single equivalent conductor by making it of proper size and position. Zero phase sequence impedance is defined as the ratio of the voltage drop along the three wires to the current in one wire. The factor 3 thus appears.

Finally for a twin circuit line with return circuits assumed below the ground there is obtained, referring to Fig. 28

$$\mathbf{E}_o = \mathbf{I}_{ao}\,\mathbf{Z}_{aa} + \mathbf{I}_{bo}\,\mathbf{Z}_{ab}$$

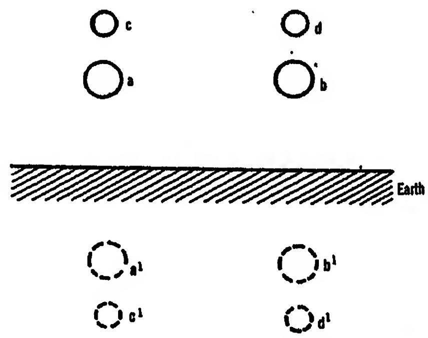


FIG. 30—EQUIVALENT CONDUCTOR ARRANGEMENT OF A DOUBLE-CIRCUIT LINE WITH GROUND WIRES

where
$\mathbf{E}_o$ is the zero phase sequence voltage induced along conductor a
$\mathbf{I}_{ao}$ is the zero phase sequence current in a
$\mathbf{I}_{bo}$ is the zero phase sequence current in b

$$\mathbf{Z}_{aa} = j\,6\,\omega\,L \log \frac{a\,a'}{G_s}$$

$$\mathbf{Z}_{ab} = j\,6\,\omega\,L \log \frac{a\,b'}{a\,b}$$

$\omega = 2\,\pi \times$ frequency

In practical units

$$Z_{aa} = j\,0.014\,f\,L\log_{10}\frac{a\,a'}{G_s}\text{ ohms, etc.}$$

where f = frequency in cycles per second
L = length of line in miles

L = length of line
$a\,a'$ = geometric mean distance from a to its assumed return conductor
$a\,b'$ = geometric mean distance from a to the return conductor of b
$a\,b$ = geometric mean distance from a to b
G_s = geometric mean distance from a to itself.

For a round wire G_s = 0.779 r where r is radius of the round wire.

To find G_s[12,13,14] for the case of three round wires in parallel making up one conductor or line (for zero phase sequence calculation) it may be noted that

$$G_s = \sqrt[9]{D_1^2\,D_2^2\,D_3^2\,r^3\,(.779)^3}$$

where D_1, D_2, and D_3 are the respective distances between the centers of the three wires.

The geometric mean distance between two such conductors is the n^2 root of the product of n^2 terms consisting of all the distances from the wires of one conductor to the wires of the other.

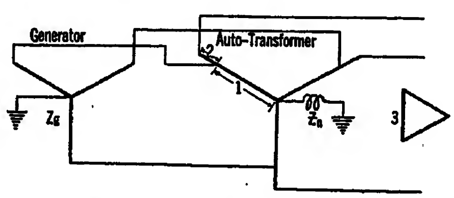


FIG. 31—DIAGRAM SHOWING A GENERATOR CONNECTED TO A STEP-UP AUTO TRANSFORMER, WITH A TERTIARY WINDING

Appendix V

PART B

METHOD OF DERIVING FORMULAS IN TABLE

Example (a). A single circuit line without ground wires with terminal transformers grounded through impedance is shown in Table II, case I, and Fig. 27.

As the zero-phase sequence impedance of a system, viewed from a point of fault, is low in the neighborhood of any grounded neutral transformer, the magnitude of the ground current will depend upon the location of the fault along the line. Referring to case (1) the fault is located at a distance K from the generator transformer and assuming that the ground current divides as shown, the two equations for the zero-phase sequence voltage may be written as follows:

$$\mathbf{V}_o = \mathbf{I}_a\,[(1 - K)\,\mathbf{Z}_{aa} + \mathbf{Z}_{tb} + 3\,\mathbf{Z}_{nb}] = \mathbf{I}_a\,\mathbf{A} \tag{28}$$

$$\mathbf{V}_o = (\mathbf{I}_g - \mathbf{I}_a)\,[K\,\mathbf{Z}_{aa} + \mathbf{Z}_{ta} + 3\,\mathbf{Z}_{na}] = (\mathbf{I}_g - \mathbf{I}_a)\,\mathbf{B} \tag{29}$$

solving for $\mathbf{I}_a$ and substituting in Equation (28)

$$\mathbf{V}_o = \mathbf{I}_g\,\frac{\mathbf{A}\,\mathbf{B}}{\mathbf{A} + \mathbf{B}} \tag{30}$$

and

$$\mathbf{Z}_o = \frac{\mathbf{V}_o}{\mathbf{I}_g} = \frac{\mathbf{A}\,\mathbf{B}}{\mathbf{A} + \mathbf{B}} \tag{31}$$

Example (b). A double circuit line without ground wires, with high-tension buses and terminal transformers grounded through impedance is shown in Case II and Fig. 28.

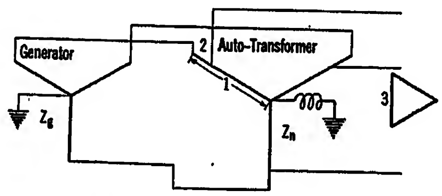


FIG. 32—DIAGRAM OF A GENERATOR CONNECTED TO A STEP-DOWN AUTO-TRANSFORMER, WITH A TERTIARY WINDING

As in example (a), the zero-phase sequence impedance varies with the position of the fault along the line. Equations for the zero-phase sequence voltage from the point of fault to ground may be written as follows:

$$\mathbf{V}_o = \mathbf{Z}_a\,(\mathbf{I}_g - \mathbf{I}_a - \mathbf{I}_b) + K\,\mathbf{Z}_{aa}\,(\mathbf{I}_g - \mathbf{I}_a) - K\,\mathbf{Z}_{ab}\,\mathbf{I}_b \tag{32}$$

$$\mathbf{V}_o = \mathbf{Z}_b\,(\mathbf{I}_a + \mathbf{I}_b) + (1 - K)\,\mathbf{Z}_{aa}\,\mathbf{I}_a + (1 - K)\,\mathbf{Z}_{ab}\,\mathbf{I}_b \tag{33}$$

Equating the zero-phase voltages over the two paths between the high-tension buses.

$$\mathbf{Z}_{aa}\,\mathbf{I}_a + \mathbf{Z}_{ab}\,\mathbf{I}_b - K\,\mathbf{Z}_{aa}\,\mathbf{I}_g = \mathbf{Z}_{ab}\,\mathbf{I}_a + \mathbf{Z}_{aa}\,\mathbf{I}_b + K\,\mathbf{Z}_{ab}\,\mathbf{I}_g$$

and

$$\mathbf{I}_o = \mathbf{I}_a - K\,\mathbf{I}_g \tag{34}$$

Substituting Equation (34) in Equations (32) and (33) and collecting terms

$$\mathbf{V}_o = \mathbf{C}\,\mathbf{I}_a + \mathbf{D}\,\mathbf{I}_g \tag{35}$$

$$\mathbf{V}_o = \mathbf{E}\,\mathbf{I}_a + \mathbf{F}\,\mathbf{I}_g \tag{36}$$

where

$$\mathbf{C} = -[2\,\mathbf{Z}_a + K\,(\mathbf{Z}_{aa} + \mathbf{Z}_{ab})] \tag{37}$$

$$\mathbf{D} = [\mathbf{Z}_a\,(1 + K) + K\,(\mathbf{Z}_{aa} + K\,\mathbf{Z}_{ab})] \tag{38}$$

$$\mathbf{E} = [2\,\mathbf{Z}_b + (1 - K)\,(\mathbf{Z}_{aa} + \mathbf{Z}_{ab})] \tag{39}$$

$$\mathbf{F} = -[K\,\mathbf{Z}_b + (1 - K)\,K\,\mathbf{Z}_{ab}] \tag{40}$$

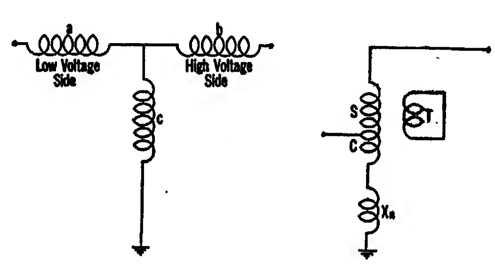


FIG. 32A—THE EQUIVALENT CIRCUIT FOR THE ZERO-PHASE IMPEDANCE OF AN AUTO-TRANSFORMER

Subtracting Equation (35) from (36)

$$\mathbf{I}_a = \frac{\mathbf{F} - \mathbf{D}}{\mathbf{C} - \mathbf{E}}\,\mathbf{I}_g \tag{41}$$

Substituting (41) in (35)

$$V_o = \frac{C\,F - D\,E}{C - E}\,I_g$$

Therefore

$$Z_o = \frac{V_o}{I_g} = \frac{C\,F - D\,E}{C - E} \tag{42}$$

Example (c). Impedance of transmission lines, with ground wires.

The preceding examples have been presented for circuits without ground wires. The same formulas apply for circuits with ground wires if the coefficients Z_{aa}, Z_{ab}, etc., are respectively replaced by Z_{aa}', Z_{ab}', etc., which account for the change in flux linkages due to the current.

A *single circuit line*, equipped with ground wires, is shown in Fig. 29. The three conductors and ground wires have been reduced to an equivalent conductor and ground wire. The return conductors are indicated by primed letters.

TABLE II

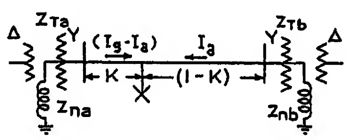
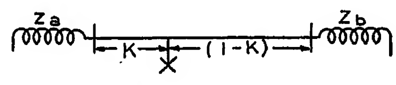
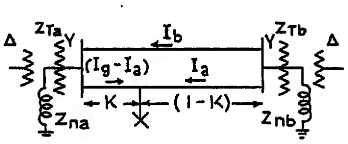
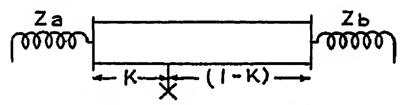
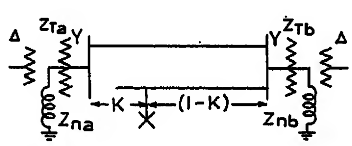
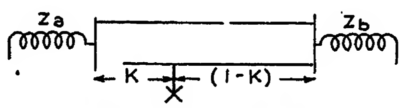
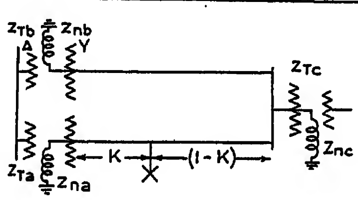
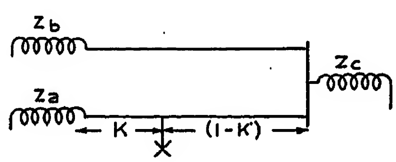
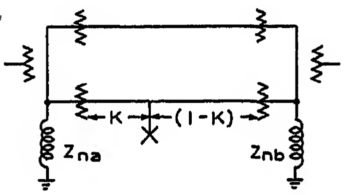
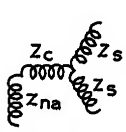
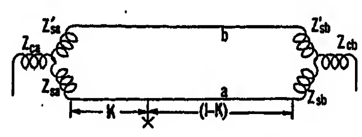
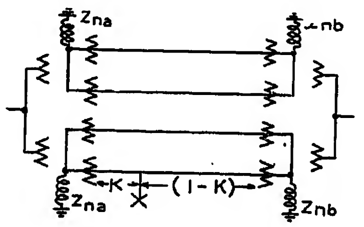
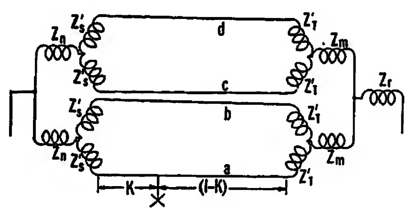
Case No.	Apparatus connections in single line diagram	Simplified zero phase sequence reactance diagram	Zero phase sequence reactance viewed from the point of fault
1		 $Z_a = Z_{Ta} + 3\,Z_{na}$ $Z_b = Z_{Tb} + 3\,Z_{nb}$	$Z_o = \frac{A\,B}{A + B}$ where $A = Z_a + K\,Z_{aa}$ $B = Z_b + (1 - K)\,Z_{aa}$
2		 $Z_a = Z_{Tb} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$ $Z_b = T_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$	$Z_o = \frac{C\,F - D\,E}{C - E}$ where $C = -[2\,Z_a + K\,(Z_{aa} + Z_{ab})]$ $D = (1 + K)\,Z_a + K\,(Z_{aa} + K\,Z_{ab})$ $E = (2\,Z_b + (1 - K)\,(Z_{aa} + Z_{ab})$ $F = -[K\,Z_b + (1 - K)\,K\,Z_{ab}]$
3		 $Z_a = Z_{Ta} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$ $Z_b = Z_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$	$Z_o = \frac{G\,J - H\,I}{G - I}$ where $G = Z_b + (1 - K)\,Z_{ab}$ $H = Z_b + (1 - K)\,Z_{aa}$ $I = -[Z_a + Z_{aa} - (1 - K)\,Z_{ab}]$ $J = (1 - K)\,(Z_{aa} - Z_{ab})$
4		 $Z_a = Z_{Ta} + 3\,Z_{na};\ Z_{aa} = Z_{bb}$ $Z_b = Z_{Tb} + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$ $Z_c = Z_{Tc} + 3\,Z_{nc}$	$Z_o = \frac{Q\,N - L\,M}{Q - M}$ where $Q = Z_a + K\,(Z_{aa} - P\,Z_{ab})$ $L = Z_a + K\,(Z_{aa} - O\,Z_{ab})$ $M = (1 - K)(Z_{aa} - P\,Z_{ab}) + (1 - P)Z_c$ $N = (1 - K)\,O\,Z_{ab} + O\,Z_c$ $O = \frac{K\,(Z_{ab} - Z_{aa}) - Z_a}{Z_b + Z_{aa} - Z_{ab}}$ $P = \frac{Z_{ab} - Z_{aa} - Z_a}{Z_b + Z_{aa} - Z_{ab}}$
5	 Note: Resolve double winding transformers into  where Z_c is usually negative.	 $Z_{ca} = Z_c + 3\,Z_{na};\ Z_{aa} = Z_{bb}$ $Z_{cb} = Z_c + 3\,Z_{nb};\ Z_{ab} = Z_{ba}$ Z_{sa}' is distinguished from Z_{sa} to allow for any lumped constants which might exist and destroy the symmetry.	$Z_o = \frac{R\,U - S\,T}{R - T}$ where $R = -[Z_{ca} + Z_{sa} + K\,(Z_{aa} + W\,Z_{ab}) + W\,Z_{ca}]$ $S = Z_{ca} + Z_{sa} + K\,(Z_{aa} + Y\,Z_{ab}) + Y\,Z_{ca}$ $T = Z_{cb} + Z_{sb} + (1 - K)\,(Z_{aa} + W\,Z_{ab}) + W\,Z_{cb}$ $U = -[Y\,Z_{cb} + (1 - K)\,Y\,Z_{ab}]$ $V = Z_{sb}' + Z_{aa} + Z_{sa}' - Z_{ab}$ $W = \frac{Z_{sb} + Z_{aa} + Z_{sa} - Z_{ab}}{V}$ $Y = \frac{Z_{sa} + K\,(Z_{aa} - Z_{ab})}{V}$

TABLE II—*Continued*

Case No.	Apparatus connections in single line diagram	Simplified zero phase sequence reactance diagram	Zero phase sequence reactance viewed from the point of fault
6	 Note: Double winding transformers reduced as in (5). Two double circuit lines considered.	 $Z_n = Z_T + 3\,Z_{na}$ $Z_m = Z_T + 3\,Z_{nb}$ $Z_{aa} = Z_{bb} = Z_{cc} = Z_{dd}$ $Z_{ab} = Z_{ba} = Z_{cd} = Z_{dc}$ $Z_{ac} = Z_{bd} = Z_{ca} = Z_{db}$ Z_s' and Z_T' are distinguished from Z_s and Z_T to allow for any lumped constants which might exist and destroy the symmetry. Z_r is added for flexibility.	$Z_o = \dfrac{\begin{vmatrix} a & -a & c & d & q \\ e & f & -f & -e & r \\ -d & -c & a & z & s \\ g & h & i & j & t \\ l & m & n & p & o \end{vmatrix}}{\begin{vmatrix} a & -a & c & d \\ e & f & -f & e \\ -d & -c & a & z \\ g & h & i & j \end{vmatrix}}$ Where $a = Z_s' + Z_{aa} + Z_T' - Z_{ab}$ $c = Z_{ac} - Z_{bc}$ $d = Z_{ad} + Z_{bd}$ $e = Z_n + Z_m + Z_{ab} - Z_{ac}$ $f = Z_n + Z_s' + Z_{aa} + Z_T' + Z_m - Z_{bc}$ $g = Z_{ad} + Z_r$ $h = Z_{ac} + Z_r$ $i = Z_n + Z_m + Z_{ab} + Z_r$ $j = Z_n + Z_m + Z_s + Z_T + Z_r + Z_{aa}$ $l = (1-K)\,Z_{ad} + Z_r$ $m = (1-K)\,Z_{ac} + Z_r$ $n = (1-K)\,Z_{ab} + Z_m + Z_r$ $o =$ Zero $p = (1-K)\,Z_{aa} + Z_T + Z_m + Z_r$ $q = K\,Z_{bd} - K\,Z_{ad}$ $r = Z_n + K\,Z_{ab} - K\,Z_{ac}$ $s = Z_s + K\,Z_{aa} - K\,Z_{ab}$ $t = -Z_n - Z_s - K\,Z_{aa}$ $z = Z_{ab} - Z_s - Z_{aa} - Z_T$
7	Same as (1) but with ground wires.	Same as (1)	$Z_o = \dfrac{A'\,B'}{A' + B'}$ where $A' = Z_a + K\,(Z_{aa}')^2$ $B' = Z_b + (1-K)\,Z_{aa}'$ and $Z_{aa}' = \dfrac{Z_{aa}\,Z_{gg} - (Z_{ga})^2}{Z_{gg}}$
8	Same as (2) but with ground wires over each circuit.	Same as (2)	$Z_o = \dfrac{C'\,F' - D'\,E'}{C' - E'}$ where $C' = -[2\,Z_a + K\,(Z_{aa}'' + Z_{ab}'')]$ $D' = Z_a\,(1+K) + K\,(Z_{aa}'' + K\,Z_{ab}'')$ $E' = 2\,Z_b + (1-K)\,(Z_{aa}'' + K\,Z_{ab}'')$ $F' = -[K\,Z_b + (1-K)\,K\,Z_{ab}'']$ See Appendix V part B for Evaluation of Z_{aa}'' and Z_{bb}''

Writing simultaneous zero-phase sequence voltage equations

$$\mathbf{V}_{oa} = \mathbf{Z}_{ag}\,\mathbf{I}_g + \mathbf{Z}_{aa}\,\mathbf{I}_a \tag{43}$$

$$\mathbf{V}_{og} = \mathbf{Z}_{gg}\,\mathbf{I}_g + \mathbf{Z}_{ga}\,\mathbf{I}_a \tag{44}$$

but

$$\mathbf{Z}_{ag} = \mathbf{Z}_{ga}$$

$$\mathbf{V}_{og} = 0$$

solving

$$\mathbf{I}_a = \frac{-\,\mathbf{V}_{oa}\,\mathbf{Z}_{gg}}{(\mathbf{Z}_{ga})^2 - \mathbf{Z}_{aa}\,\mathbf{Z}_{gg}} \tag{45}$$

This gives

$$\mathbf{V}_{oa} = \mathbf{I}_a\,\mathbf{Z}_{aa}'$$

where

$$\mathbf{Z}_{aa}' = \frac{\mathbf{Z}_{aa}\,\mathbf{Z}_{gg} - (\mathbf{Z}_{ga})^2}{\mathbf{Z}_{gg}} \tag{46}$$

When $\mathbf{Z}_{aa}'$ is substituted in formulas (28) and (29) the correct coefficients for a single circuit line with ground wires are obtained.

A *double circuit line* equipped with ground wires is shown in Fig. 30. The three conductors and ground wires of each line have been reduced to equivalent conductors and ground wires. The return conductors are indicated by primed letters.

The resulting modified coefficients are

$$\mathbf{Z}_{aa}'' = \mathbf{Z}_{aa} - \mathbf{Z}_{ac}\,\mathbf{J}_{ac} - \mathbf{Z}_{aa}\,\mathbf{J}_{bc} \tag{47}$$

$$\mathbf{Z}_{ab}'' = \mathbf{Z}_{ab} - \mathbf{Z}_{ac}\,\mathbf{J}_{bc} - \mathbf{Z}_{ad}\,\mathbf{Z}_{ac} \tag{48}$$

where

$$\mathbf{J}_{ac} = \frac{\mathbf{Z}_{ac}\,\mathbf{Z}_{cc} - \mathbf{Z}_{ad}\,\mathbf{Z}_{cd}}{\mathbf{Z}_{cc}^2 - \mathbf{Z}_{cd}^2} \tag{49}$$

$$\mathbf{J}_{bc} = \frac{\mathbf{Z}_{ad}\,\mathbf{Z}_{cc} - \mathbf{Z}_{cd}\,\mathbf{Z}_{ac}}{\mathbf{Z}_{cc}^2 - \mathbf{Z}_{cd}^2} \tag{50}$$

Equations (47), (48), (49), and (50) have been developed in Park and Bancker's paper.[1] When $\mathbf{Z}_{aa}''$ and $\mathbf{Z}_{ab}''$ are substituted for $\mathbf{Z}_{aa}$ and $\mathbf{Z}_{ab}$ in formulas (37)-(40) they give coefficients which are correct for a double circuit line with ground wires.

TABLE III

CONSTANTS FOR STEP-BY-STEP CALCULATIONS

Driving Point Impedances

Machine	M	k	E	δ_0	During fault Z	During fault θ	After fault Z	After fault θ
1	7.50	7.20	1.045	19.98°	0.4215	89.83°	0.890	89.19°
2	105.0	0.514	1.015	−12.29°	0.5703	89.44°	0.816	88.16°
3	0.625	86.4	1.437	− 4.37°	2.504	88.95°	2.578	88.64°

Transfer impedances

Impedance	During fault Z	During fault θ	After fault Z	After fault θ
Z_{12}	2.178	91.21°	1.059	91.50°
Z_{13}	14.68	94.67°	7.15	94.97°
Z_{23}	7.10	94.50°	4.56	94.95°

Torque components

	Total before fault	During fault	After fault
T_{11}	0.7917	$2.59 \sin 0.17° = 0.0077$	$1.227 \sin 0.81° = .0174$
T_{12}		$0.487 \sin (\delta_{12} + 1.21°)$	$1.002 \sin (\delta_{12} + 1.50°)$
T_{13}		$0.1023 \sin (\delta_{13} + 4.67°)$	$0.210 \sin (\delta_{13} + 4.97°)$
T_{22}	−0.5833	$1.806 \sin 0.56° = 0.0177$	$1.263 \sin 1.84° = .0406$
T_{21}		$-0.487 \sin (\delta_{12} - 1.21°)$	$-1.002 \sin (\delta_{12} - 1.50°)$
T_{23}		$-0.2054 \sin (\delta_{32} - 4.50°)$	$-0.320 \sin (\delta_{32} - 4.95°)$
T_{33}	0.0	$0.825 \sin 1.05° = .0151$	$0.802 \sin 1.36° = .0190$
T_{31}		$-0.1023 \sin (\delta_{13} - 4.67°)$	$-0.210 \sin (\delta_{13} - 4.97°)$
T_{32}		$0.205 \sin (\delta_{32} + 4.50°)$	$0.320 \sin (\delta_{32} + 4.95°)$

Appendix VI

The Zero-Phase Sequence Impedance of an Auto-Transformer

In making stability studies on a large system the zero-phase sequence network plays an important part in the equivalent circuit if ground faults are encountered.

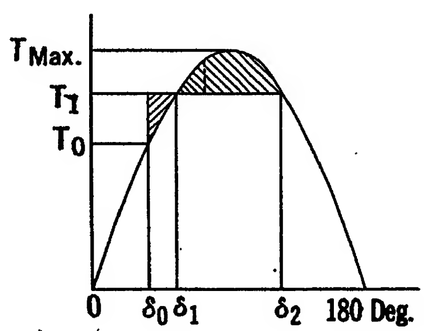


Fig. 33—Torque-Angle Diagram showing Effect of a Suddenly Applied Load

Zero-phase sequence networks often involve auto-transformers which prove troublesome to evaluate correctly. This appendix derives a formula for the zero-phase sequence impedance of a three-phase bank of auto-transformers as viewed from the load side, with the neutral grounded through an impedance and a generator connected to the other side. The generator may also be grounded through an impedance. See Figs. 31 and 32.

The following equations may be written.[22]

$$\left.\begin{aligned} \mathbf{v}_1 &= \mathbf{z}_{11}\,\mathbf{i}_1 + \mathbf{z}_{12}\,\mathbf{i}_2 + \mathbf{z}_{13}\,\mathbf{i}_3 + \mathbf{E} \\ \mathbf{v}_2 &= \mathbf{z}_{21}\,\mathbf{i}_1 + \mathbf{z}_{22}\,\mathbf{i}_2 + \mathbf{z}_{23}\,\mathbf{i}_3 + \mathbf{E} \\ \mathbf{v}_3 &= \mathbf{z}_{31}\,\mathbf{i}_1 + \mathbf{z}_{32}\,\mathbf{i}_2 + \mathbf{z}_{33}\,\mathbf{i}_3 + \mathbf{E} \end{aligned}\right\} \quad (51)$$

$$\mathbf{i}_1 + \mathbf{i}_2 + \mathbf{i}_3 = 0$$

In these equations the quantities are expressed as per unit quantities all on a common kv-a. base and on their own voltage base, as is common in transformer practise. The impedance $\mathbf{z}_{11}$ is the self impedance of winding 1 and $\mathbf{z}_{12}$ is the mutual impedance from winding 1 to winding 2. Each of these quantities considers

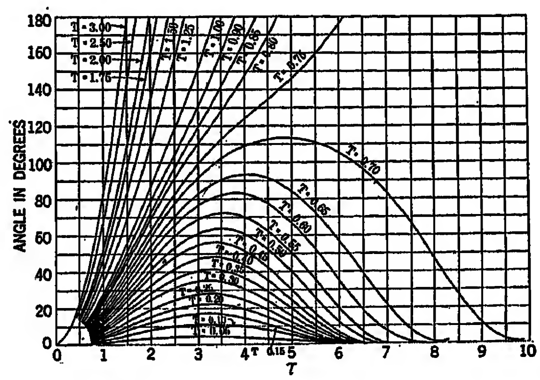


Fig. 34—Angle-Time Curves for $\dfrac{T_o}{T_m} = 0.00$

only the flux in the air. $\mathbf{E}$ is a per-unit quantity representing the voltage induced in each winding by the flux in the iron.

To eliminate $\mathbf{E}$ subtract and the result is

$$\left.\begin{aligned} \mathbf{v}_1 - \mathbf{v}_2 &= \mathbf{z}_1\,\mathbf{i}_1 - \mathbf{z}_2\,\mathbf{i}_2 \\ \mathbf{v}_2 - \mathbf{v}_3 &= \mathbf{z}_2\,\mathbf{i}_2 - \mathbf{z}_3\,\mathbf{i}_3 \\ \mathbf{v}_3 - \mathbf{v}_1 &= \mathbf{z}_3\,\mathbf{i}_3 - \mathbf{z}_1\,\mathbf{i}_1 \end{aligned}\right\} \quad (52)$$

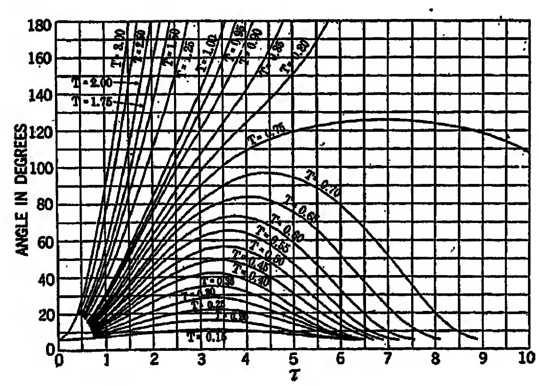


Fig. 35—Angle-Time Curves for $\dfrac{T_o}{T_m} = 0.10$

where

$$\left.\begin{aligned} \mathbf{z}_1 &= \mathbf{z}_{11} - \mathbf{z}_{12} - \mathbf{z}_{13} + \mathbf{z}_{23} \\ \mathbf{z}_2 &= \mathbf{z}_{22} - \mathbf{z}_{12} - \mathbf{z}_{23} + \mathbf{z}_{12} \\ \mathbf{z}_3 &= \mathbf{z}_{33} - \mathbf{z}_{13} - \mathbf{z}_{23} + \mathbf{z}_{12} \end{aligned}\right\} \quad (53)$$

The measured impedances in a transformer are $\mathbf{z}_{1-2}$, $\mathbf{z}_{1-3}$, and $\mathbf{z}_{2-3}$ where $\mathbf{z}_{1-2}$ for example is the per-unit impedance found by short circuiting winding 2 and measuring current and volts at winding 1.

TABLE IV

t	0	.05	.10	.15	.20		.20	.25	.30	.35	.40	.45	.50	.55	.60
$k_1 T_{a1} = 7.20\ T_{a1}$	0	1.68	3.23	2.90	2.46			.01	−2.54	−2.77	−2.77	−2.75	−2.80	−2.85	−2.70
$\Delta\ \delta_1$	0	1.68	4.91	7.81	10.27		10.27	10.28	7.74	4.97	2.20	−.55	−3.35	−6.20	−8.90
δ_1	19.98	21.66	26.57	34.38	44.65		44.65	54.93	62.67	67.64	69.84	69.29	65.94	59.74	50.84
$k_2 T_{a2} = .514\ T_{a2}$	0	−.09	−.17	−.15	−.13			.002	.16	.23	.27	.28	.27	.23	.18
$\Delta\ \delta_2$	0	−.09	−.26	−.41	−.54		−.54	−.54	−.38	−.15	.12	.40	.67	.90	1.08
δ_2	−12.29	−12.38	−12.64	−13.05	−13.59		−13.59	−13.05	−13.43	−13.58	−13.46	−13.06	−12.39	−11.49	−10.41
$k_3 T_{a3} = 86.4\ T_{a3}$	0	−1.07	−1.45	.26	2.10			6.60	6.30	−.60	−7.14	−9.57	−6.82	−.22	6.42
$\Delta\ \delta_3$	0	−1.07	−2.52	−2.26	−.16		−.16	6.44	12.74	12.14	5.00	−4.57	−11.39	−11.61	−5.19
δ_3	−4.37	−5.44	−7.96	−10.22	−10.38		−10.38	−3.94	8.80	20.94	25.94	21.37	9.96	−1.65	−6.84
$\delta_1 - \delta_2 = \delta_{12}$	32.27	34.04	39.21	47.43	58.24		58.24	67.98	76.10	81.22	83.30	82.35	78.33	71.23	
$\delta_1 - \delta_3 = \delta_{13}$	24.35	27.10	34.53	44.60	55.03		55.03	58.87	53.87	46.70	43.90	47.92	55.98	61.39	
$\delta_3 - \delta_2 = \delta_{32}$	7.92	6.94	4.68	2.83	3.21		3.21	9.11	22.23	34.52	39.40	34.43	22.35	9.84	
Constant α_{12}	−1.21						−1.50								
Constant α_{13}	−4.67						−4.97								
Constant α_{23}	−4.50						−4.95								
$\delta_{12} - \alpha_{12}$	33.48	35.25	40.42	48.64	59.45		59.74	69.48	77.60	82.72	84.80	83.85	79.83	72.73	
$\delta_{13} - \alpha_{13}$	29.02	31.77	39.20	49.27	59.70		60.00	63.84	58.84	51.67	48.87	52.89	60.95	66.36	
Sin $(\delta_{12} - \alpha_{12})$	.5517	.577	.648	.751	.861		.864	.937	.977	.992	.996	.994	.984	.955	
Sin $(\delta_{13} - \alpha_{13})$	.4851	.526	.632	.758	.863	.277	.866	.898	.856	.784	.753	.798	.874	.916	
$T_{12} = K_{12} \sin (\delta_{12} - \alpha_{12})$	.2687	.281	.316	.366	.419	−.274	.866	.939	.979	.994	.998	.996	.987	.957	
$T_{13} = K_{13} \sin (\delta_{13} - \alpha_{13})$	.0496	.054	.065	.078	.088	2/.003	.182	.188	.180	.165	.158	.168	.184	.192	
$T_{a1} = T_1 - T_{11} - T_{12} - T_{13}$	.4657	.449	.404	.341	.277	.0016	−.274	−.353	−.384	−.384	−.382	−.390	−.396	−.375	
$\delta_{12} + \alpha_{12}$	31.06	32.83	38.00	46.22	57.03		56.74	66.48	74.60	79.72	81.80	80.85	76.83	69.73	
$\delta_{32} + \alpha_{23}$	3.42	2.44	.18	−1.67	−1.29		−1.74	4.16	17.28	29.57	34.45	29.48	17.40	4.89	
Sin $(\delta_{12} + \alpha_{12})$	.5159	.542	.616	.722	.839		.836	.917	.964	.984	.990	.987	.974	.938	
Sin $(\delta_{32} + \alpha_{23})$	.0597	.043	.003	−.029	−.022	.204	−.030	.072	.297	.494	.566	.492	.299	.085	
$T_{21} = -K_{12} \sin (\delta_{12} + \alpha_{12})$	−.2512	−.264	−.300	−.352	−.408	−.197	−.838	−.919	−.966	−.986	−.992	−.990	−.976	−.941	
$T_{23} = -K_{32} \sin (\delta_{32} + \alpha_{23})$	−.0123	−.009	−.001	.006	.005	2/.007	.010	−.023	−.095	−.158	−.181	−.158	−.096	−.027	
$T_{a2} = T_2 - T_{22} - T_{21} - T_{23}$	−.3375	−.328	−.301	−.255	−.197	.0036	.204	.318	.436	.520	.549	.524	.448	.344	
$\delta_{13} + \alpha_{13}$	19.68	22.43	29.86	39.93	50.36		50.06	53.90	48.90	41.73	38.93	42.95	51.01	56.42	
$\delta_{32} - \alpha_{23}$	12.42	11.44	9.18	7.33	7.71		8.16	14.06	27.18	39.47	44.35	39.38	27.30	14.79	
Sin $(\delta_{13} + \alpha_{13})$	.3368	.382	.498	.642	.770		.767	.808	.754	.666	.628	.681	.777	.833	
Sin $(\delta_{32} - \alpha_{23})$	.2151	.198	.160	.128	.134	.046	.142	.243	.457	.636	.699	.634	.459	.255	
$T_{31} = -K_{13} \sin (\delta_{13} + \alpha_{13})$	−.0345	−.039	−.051	−.066	−.079	.107	−.161	−.170	−.158	−.140	−.132	−.143	−.163	−.175	
$T_{32} = K_{32} \sin (\delta_{32} - \alpha_{23})$	.0442	.041	.033	.026	.018	2/.153	.045	.078	.146	.203	.224	.203	.147	.082	
$T_{a3} = T_3 - T_{33} - T_{31} - T_{32}$	−.0248	−.017	.003	.024	.046	.076	.107	.073	−.007	−.083	−.111	−.079	−.003	.074	

The succeeding relations follow from combining Equations (53) with the equations representing these short circuited connections.

$$\left.\begin{aligned} \mathbf{z}_1 &= \frac{\mathbf{z}_{1-2} + \mathbf{z}_{1-3} - \mathbf{z}_{2-3}}{2} \\ \mathbf{z}_2 &= \frac{\mathbf{z}_{1-2} + \mathbf{z}_{2-3} - \mathbf{z}_{1-3}}{2} \\ \mathbf{z}_3 &= \frac{\mathbf{z}_{1-3} + \mathbf{z}_{2-3} - \mathbf{z}_{1-2}}{2} \end{aligned}\right\} \tag{54}$$

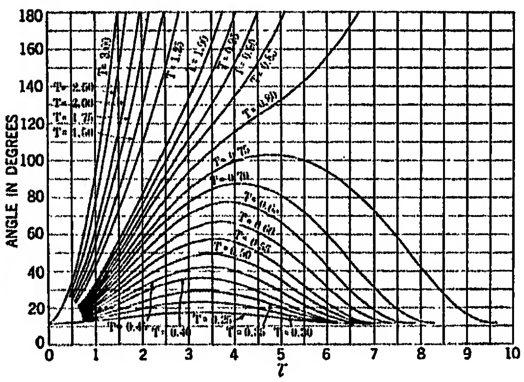


FIG. 36—ANGLE-TIME CURVES FOR $\frac{T_o}{T_m} = 0.20$

For zero-phase sequence calculations the equations may be written

$$\left.\begin{aligned} \mathbf{v}_{10} &= \mathbf{z}_{11}\,\mathbf{i}_{10} + \mathbf{z}_{12}\,\mathbf{i}_{20} + \mathbf{z}_{13}\,\mathbf{i}_{30} + E_0 \\ \mathbf{v}_{20} &= \mathbf{z}_{21}\,\mathbf{i}_{10} + \mathbf{z}_{22}\,\mathbf{i}_{20} + \mathbf{z}_{23}\,\mathbf{i}_{30} + E_0 \\ \mathbf{v}_{30} &= \mathbf{z}_{31}\,\mathbf{i}_{10} + \mathbf{z}_{32}\,\mathbf{i}_{20} + \mathbf{z}_{33}\,\mathbf{i}_{30} + E_0 \\ \mathbf{i}_{10} &+ \mathbf{i}_{20} + \mathbf{i}_{30} = 0 \\ \mathbf{v}_{30} &= 0 \end{aligned}\right\} \tag{55}$$

The latter relation is introduced because of the tertiary winding.

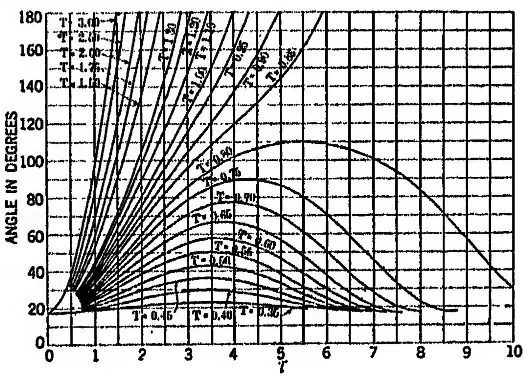


FIG. 37—ANGLE-TIME CURVES FOR $\frac{T_o}{T_m} = 0.30$

The result of simplifying is

$$\left.\begin{aligned} \mathbf{v}_{10} &= (\mathbf{z}_1 + \mathbf{z}_3)\,\mathbf{i}_{10} + \mathbf{z}_3\,\mathbf{i}_{20} \\ \mathbf{v}_{20} &= \mathbf{z}_3\,\mathbf{i}_{10} + (\mathbf{z}_2 + \mathbf{z}_3)\,\mathbf{i}_{20} \end{aligned}\right\} \tag{56}$$

To find the voltage across both windings 1 and 2 it is necessary to introduce the voltage ratio in order that the voltages may be expressed on a common voltage base before adding.

Let K be the ratio of the voltage in the winding between neutral and the generator to that in the winding between neutral and the load, at no load.

There is obtained the following set of relations, where the capital letters signify that the quantities have been expressed on a common voltage base, that of the load.

$$\left.\begin{aligned} \mathbf{V}_{so} &= \mathbf{V}_{10} + \mathbf{V}_{20} \\ \mathbf{v}_{20} &= \frac{1}{1-K}\,\mathbf{V}_{20} \\ \mathbf{v}_{10} &= \frac{1}{K}\,\mathbf{V}_{10} \\ \mathbf{i}_{20} &= (1-K)\,\mathbf{I}_{20} \\ \mathbf{i}_{10} &= K\,\mathbf{I}_{10} \end{aligned}\right\} \tag{57}$$

Combining:

$$\left.\begin{aligned} \mathbf{V}_{so} &= K^2\left(\mathbf{z}_1 + \frac{1}{K}\,\mathbf{z}_3\right)\mathbf{I}_{10} \\ &\quad + (1-K)\,[(1-K)\,\mathbf{z}_2 + \mathbf{z}_3]\,\mathbf{I}_{20} \\ \mathbf{V}_{10} &= K^2\,(\mathbf{z}_1 + \mathbf{z}_3)\,\mathbf{I}_{10} + K\,(1-K)\,\mathbf{z}_3\,\mathbf{I}_{20} \end{aligned}\right\} \tag{58}$$

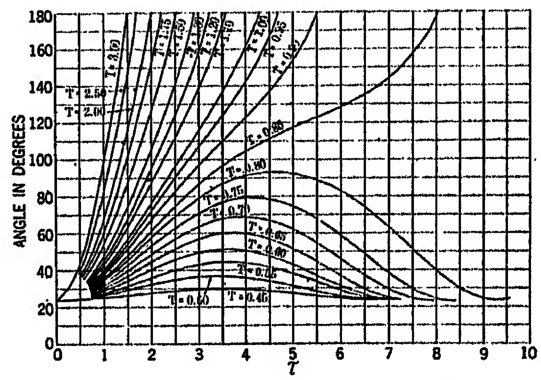


FIG. 38—ANGLE TIME CURVES FOR $\frac{T_o}{T_m} = 0.40$

Another relation is now needed and it is obtained by writing the drops through the transformer windings

$$\mathbf{z}_o = \frac{\mathbf{V}_{so} + \mathbf{I}_{10}\,K^2\,\mathbf{z}_n}{\mathbf{I}_{20}} \tag{59}$$

This gives

$$\mathbf{z}_o = K\,(1-K)\left[\frac{1-K}{K}\,\mathbf{z}_2 + \frac{\mathbf{z}_3}{K}\right] + \frac{\mathbf{I}_{10}}{\mathbf{I}_{20}}\,K^2\left[\mathbf{z}_1 + \frac{1}{K}\,\mathbf{z}_3 + \mathbf{z}_n\right] \tag{60}$$

Still another relation is now needed to find the current division and this is obtained by writing the drops through the neutral connections.

$$K^2\,(\mathbf{I}_{20} - \mathbf{I}_{10})\,\mathbf{z}_g - \mathbf{V}_{10} - \mathbf{I}_{10}\,K^2\,\mathbf{z}_n = 0 \tag{61}$$

The factor K^2 is introduced into (59) and (61) to allow for $\mathbf{Z}_g$ and $\mathbf{Z}_n$ being expressed on the generator voltage base instead of the load voltage base.

This gives

$$\frac{\mathbf{I}_{10}}{\mathbf{I}_{20}} = \frac{\mathbf{z}_g - \dfrac{(1-K)}{K}\mathbf{z}_3}{\mathbf{z}_g + \mathbf{z}_1 + \mathbf{z}_3 + \mathbf{z}_n} \tag{62}$$

Substituting (62) in (60) gives the final formula

$$\mathbf{z}_o = (1-K)^2\,\mathbf{z}_2 + \frac{\mathbf{z}_3\,[\mathbf{z}_g + (1-K)^2\,(\mathbf{z}_1 + \mathbf{z}_n)] + K^2\,\mathbf{z}_g\,[\mathbf{z}_n + \mathbf{z}_1]}{\mathbf{z}_g + \mathbf{z}_1 + \mathbf{z}_3 + \mathbf{z}_n} \tag{63}$$

In case the "series-common to common" impedance is given it may be made use of by means of the relation

$$\mathbf{z}_{1-2} = \mathbf{z}_{sc-c}\,\frac{1}{(1-K)^2}$$

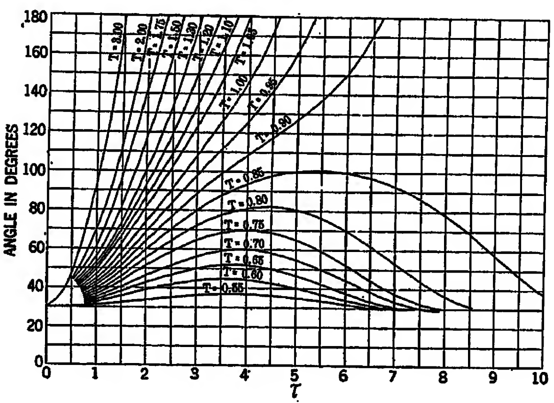


FIG. 39—ANGLE-TIME CURVES FOR $\dfrac{T_o}{T_m} = 0.50$

$\mathbf{z}_n$ and $\mathbf{z}_g$ are to be expressed on the generator voltage base and all others to be on their own voltage base. All reactances to be on a common kv-a. base.

Various kinds of neutral connections may be represented by letting $\mathbf{z}_g$ and $\mathbf{z}_n$ be finite, zero, or infinite as the case may be. In case there is no tertiary, $\mathbf{z}_3$ is infinite and substitution of this gives the correct solution. In case the neutrals are connected together and then grounded through a common impedance this impedance may be considered to be in the load circuit by expressing it on the load voltage base and adding it to the impedance found by neglecting it. It may be noted that $\mathbf{z}_n$ naturally associates itself with $\mathbf{z}_1$ in formula (63). Thus if $\mathbf{z}_1'$ be taken to include $\mathbf{z}_n$ and $\mathbf{z}_1$ the following simple form occurs

$$\mathbf{z}_o = (1-K)^2\,\mathbf{z}_2 + \frac{\mathbf{z}_3\,[\mathbf{z}_g + (1-K)^2\,\mathbf{z}_1'] + K^2\,\mathbf{z}_g\,\mathbf{z}_1'}{\mathbf{z}_1' + \mathbf{z}_3 + \mathbf{z}_g} \tag{64}$$

These results apply to step-down as well as step-up auto-transformers.

In cases where the auto transformers become part of a complicated network it is a practical necessity to have an equivalent circuit for the zero-phase sequence impedance of the auto transformer. The formula derived above may be reduced to an equivalent network by means of a method suggested by R. H. Park. This consists first in establishing the validity of the process by showing that the necessary criterion that such an equivalent circuit can be constructed in terms of per unit quantities is merely that the impedances be expressed on a common kv-a. base. Then, referring to Fig. 32A, four relations are obtained by considering each of the two branches of the equivalent circuit in Fig. 32A first open, then grounded.

Thus

$$a + c = x_{c-t} + x_n \tag{65}$$

$$b + c = x_{sc-t} + K_c^2\,x_n \tag{66}$$

$$b + \frac{a\,c}{a+c} = (1-K_c)^2\left[\frac{x_{s-c} + x_{s-t} - x_{c-t}}{2} + \frac{\left[\dfrac{x_{c-t} + x_{s-t} - x_{s-c}}{2}\right]\left[\dfrac{x_{s-c} + x_{c-t} - x_{s-t}}{2} + x_n\right]}{x_n + x_{c-t}}\right] \tag{67}$$

$$a + \frac{b\,c}{b+c} = \left(1 - \frac{1}{K_c}\right)^2\left[\frac{x_{sc-s} + x_{s-t} - x_{sc-t}}{2} + \frac{\left[\dfrac{x_{sc-t} + x_{s-t} - x_{sc-s}}{2}\right]\left[\dfrac{x_{sc-s} + x_{sc-t} - x_{s-t}}{2} + K_c^2\,x_n\right]}{K_c^2\,x_n + x_{sc-t}}\right] \tag{68}$$

Also there is

$$x_{s-c} = x_{sc-c}\left(\frac{1}{1-K_c}\right)^2 \tag{69}$$

$$x_{sc-s} = x_{sc-c}\left(\frac{K_c}{1-K_c}\right)^2 \tag{70}$$

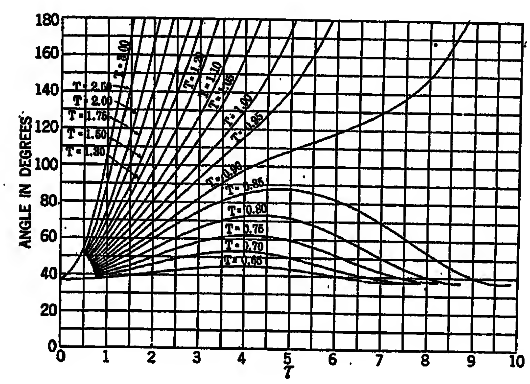


FIG. 40—ANGLE-TIME CURVES FOR $\dfrac{T_o}{T_m} = 0.60$

Where K_c is voltage in the common winding divided by voltage in the series plus common windings and x_n is expressed on the low-voltage base. The subscripts on the various reactances refer to the series, common, series common, and tertiary windings. The first two equations are written by inspection, and the second two from Formula (63).

These relations combined result in the following relation between the reactances

$$x_{s-t} = \frac{1}{1 - K_c}\left[x_{sc-t} - K_c\, x_{c-t} + \frac{K_c}{1 - K_c}\, x_{sc-c} \right] \quad (71)$$

Formula (71) combined with numbers (65), (66), and (67), (69), and (70) results in the following values for the branches of the equivalent circuit.*

$$c = \frac{x_{sc-t} + x_{c-t} - x_{sc-c}}{2} + K_c\, x_n \quad (72)$$

$$b = x_{sc-t} + K_c^2\, x_n - c \quad (73)$$

$$a = x_{c-t} + x_n - c \quad (74)$$

This gives an equivalent circuit whereby per unit reactances may be used directly and external impedances may be added to the two branches, on their own voltage base, in any amount of complexity and treated as an ordinary network.

These equations could have been obtained more directly from a knowledge of the ordinary formulas for three circuit transformers[25, 26] but it was thought best to include the full derivation in order to obtain a more complete set of relations.

*These results were first obtained by Mr. H. C. Verwoert.

Appendix VII

The following detailed data submitted for a stability study on a system would practically eliminate the necessity of making any assumptions.

(a) A single line, circuit diagram of the system under consideration as well as of adjacent systems which may be connected, giving

1. Location of, and
2. Electrical arrangement of
   - (i) Lines
   - (ii) Generators
   - (iii) Transformers
   - (iv) Reactors
   - (v) Loads
   - (vi) Grounds
   - (vii) Delta-Y grounded banks

(b) Map showing the geographical location and topography of the area which the lines traverse.

(c) Lines

1. Voltage
2. Number of circuits
3. Spacing
4. Length
5. Size of conductors—material
6. Ground wires:—number, size, material, location
7. Soil conditions, tower footings

(d) Synchronous Machines

1. Type
   - (i) Turbo generators
   - (ii) Waterwheel generators
   - (iii) Frequency sets
   - (iv) Condensers
   - (v) Synchronous motors
2. Location
3. Kv-a. capacity
4. Frequency
5. Speed
6. Short circuit ratio
7. "Potier" reactance*
8. Synchronous reactance
9. Direct and quadrature transient reactance
10. Negative phase sequence reactance
11. Zero phase sequence reactance (if grounded)
12. Single or double winding; connections
13. Normal load in operation
14. Type of excitation used
    - (i) Self excited
    - (ii) Separately excited; size, rev. per min. of exciters
    - (iii) Main field rheostats
15. Governor regulation of prime movers
16. $W R^2$ including prime movers
17. Type of regulator used

(e) Transformers

1. Kv-a. rating
2. Location
3. Number of windings
4. Step up or auto transformers
5. Arrangement of windings, Y-Y, etc.
6. Reactances, particularly auto-transformers
7. Neutral impedances
8. Grounding transformers

(f) Loads

1. Actual load on each bus
2. Connected load on each bus
3. Location of load centers
4. Nature of loads if possible
5. Peak load
6. Load factor
7. Location of load grounds
8. Per cent resistance, induction and synchronous connected load

(g) Bus Arrangements

1. High-voltage buses
2. Low-voltage buses
3. Generators on each bus
4. Load on each bus
5. Bus reactors
6. Voltage normally maintained on the various buses
7. Interconnections with other systems

(h) Relaying

1. For fault conditions what time of breaker opening is expected

*The reactance determined by the Potier method, *i. e.*, the reactance used in calculating regulation. This was formerly referred to as "the reactance" or the leakage reactance.

2. What normal switching operations are likely to occur
3. Overload relay settings

(i) Fault conditions

Information as to the type of faults encountered and the behavior of the system under fault conditions would be useful in directing the stability study in the proper channel.

1. 1-conductor-to-ground fault
2. 2-conductor-to-ground fault
3. Conductor-to-conductor fault
4. Three-phase fault
5. Major switching operations
6. Frequency of small oscillations

Appendix VIII

Simplified Methods in the Ideal Case

The fundamental equation for rotor motion in an ideal case has been given,[1] referring to Fig. 33, as

$$\frac{M}{2\pi f}\;\frac{d^2\delta}{dt^2} = T_1 - T_m \sin\delta \qquad (75)$$

$$T_m = \frac{\Psi_a \Psi_b}{x} \qquad (76)$$

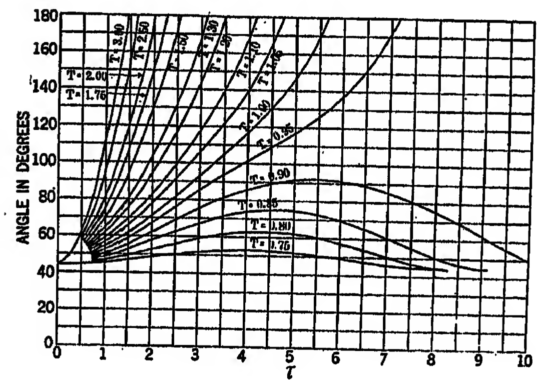


Fig. 41—Angle-Time Curves for $\dfrac{T_o}{T_m} = 0.70$

Ψ_a, Ψ_b = Per unit linkages in the two machines
x = Per unit reactance between the linkages
T_1 = New per unit total torque
M = Time to come to rest with normal torque applied
δ = Electrical angle between machine linkages
f = Normal frequency
t = Time

This equation results from substituting

$$M = \frac{I\,\omega^2}{\omega\,T_n} \qquad (77)$$

where I is moment of inertia
ω is normal speed of rotor
T_n is normal torque

in the relation that torque equals the product of moment of inertia and angular acceleration, taking due account of the relation between mechanical and electrical angle.

Curves for the solution of this equation have been given but it has been thought desirable to make new ones in greater detail so as to simplify the interpolation.

In order to do this the Integraph[20] at the Massachusetts Institute of Technology was used.

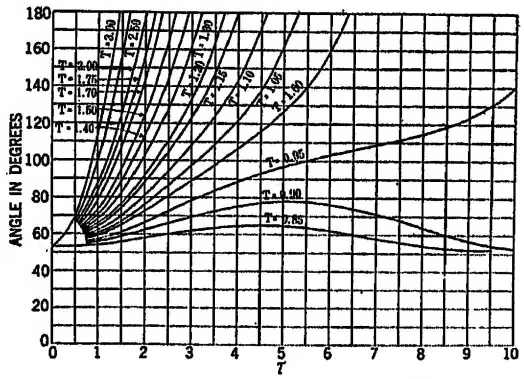


Fig. 42—Angle-Time Curves for $\dfrac{T_o}{T_m} = 0.80$

Let

$$\tau = t\sqrt{\frac{2\pi f}{M}\,T_m} \qquad (78)$$

and

$$T = T_1/T_m \qquad (79)$$

This gives

$$\frac{d^2\delta}{d\tau^2} + \sin\delta = T \qquad (80)$$

Equation (80) is in form for direct solution on the integraph and the curves shown in Fig. 34 to Fig. 43 were

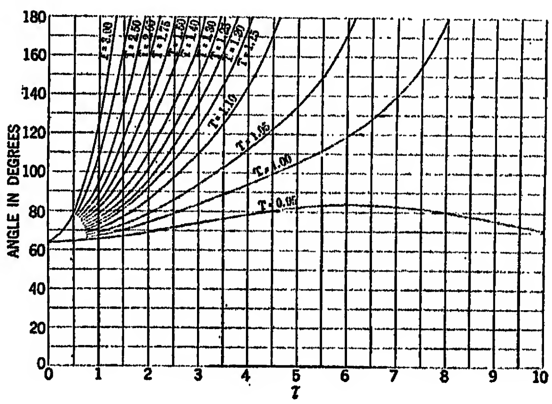


Fig. 43—Angle-Time Curves for $\dfrac{T_o}{T_m} = 0.90$

obtained, where δ_0 is the initial angle, T_0 the initial torque and

$$\sin\delta_0 = \frac{T_0}{T_m}$$

For small excursions along the torque angle curves Equation (80) may be written

$$p^2 \Delta \delta + m^2 \Delta \delta = \Delta T \, 1 \qquad (81)$$

where

$$p = \frac{d}{d(\Delta \tau)}$$

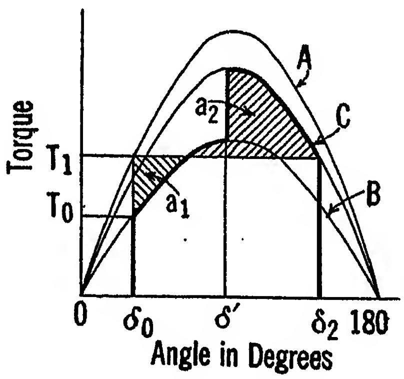


FIG. 44—TORQUE-ANGLE DIAGRAMS SHOWING THE EFFECT OF CLEARING A FAULT BY OPENING A PARALLEL LINE

m^2 = slope of curve at some average point in the excursion but may be taken at δ_o in the absence of other information. Making this assumption in the ideal case $m^2 = \cos \delta_o$

$\Delta \delta$ = Increase in angle from δ_o

$$\Delta \tau = \Delta t \sqrt{\frac{2 \pi f}{M} T_m} \qquad (78a)$$

$$\Delta T = T - \frac{T_o}{T_m} = T - \sin \delta.$$

Δt = time of travel from δ_o

δ_o is angle of rotor at beginning of excursion, corresponding to a torque of T_o

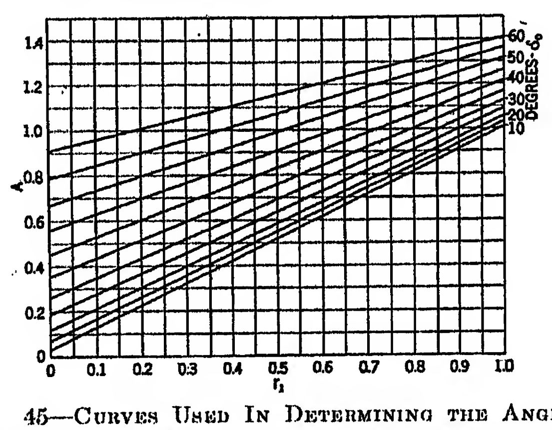


FIG. 45—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART I

Solving

$$\Delta \delta = \frac{\Delta T}{m^2} \, \frac{1}{\left(\frac{p}{m}\right)^2 + 1} \, 1 \qquad (82)$$

which gives

$$\Delta \delta = \frac{\Delta T}{m^2} \left[1 - \cos m \, \Delta \tau\right] \qquad (83)$$

and

$$\Delta \tau = \frac{1}{m} \cos^{-1}\left(1 - \frac{m^2 \, \Delta \delta}{\Delta T}\right) \qquad (84)$$

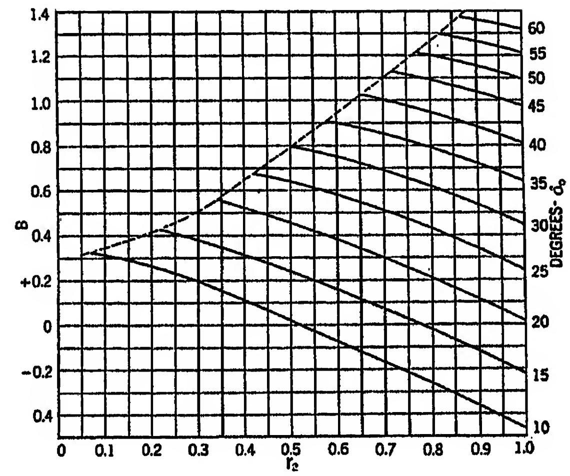


FIG. 46—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART II

In case $m = 0$ this reduces to

$$\Delta \delta = \Delta T \, \frac{(\Delta \tau)^2}{2} \qquad (85)$$

$$\Delta \tau = \sqrt{\frac{2 \, \Delta \delta}{\Delta T}} \qquad (86)$$

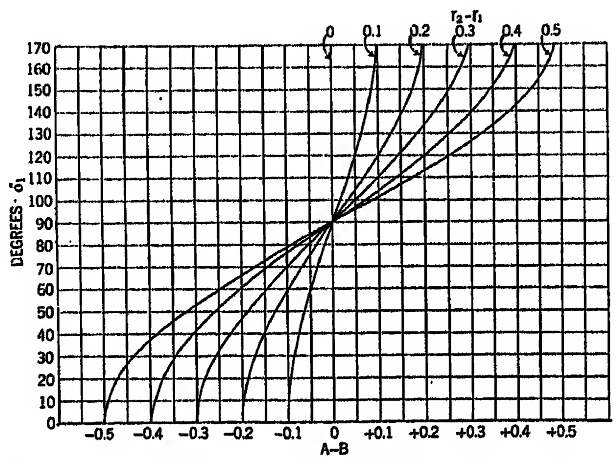


FIG. 47—CURVES USED IN DETERMINING THE ANGLE AT WHICH SWITCHING MUST OCCUR TO MAINTAIN STABILITY. PART III

Time may be obtained from Equations (84) and (86) by applying Equation (78) or (78a)

The Angle at Which Switching of the Fault Must Occur for a Given Initial Torque and Angle to Achieve Stability

Consider the ideal case of a generator delivering power to a motor over two or more interconnecting lines. The torque-angle characteristics are shown on Fig. 44, the equations of which are

$$T = \frac{\Psi_a \Psi_b}{x} \sin \delta$$

where x equals the reactance between the two machines, a different value for each condition. T_1 and δ_o are the initial torque and angle at which the generator is operating before the fault occurs. During the fault, the generator is operating on the new torque-angle curve B and with the initial angle of δ_o. A torque of only T_o can be maintained but, with the prime mover delivering T_1, the difference between T_1 and T_o is available for acceleration. As the generator rotor accelerates, there will be some angle δ' where if switching occurs, the generator will just be stable. Referring to the torque angle characteristic of Fig. 44 the area a_1 is available for accelerating the rotor while the area a_2 is available for deceleration. The criterion for stability limit is that switching occurs at δ' so that $a_2 = a_1$. The maximum angle δ' may be obtained from the equation[1]

$$\cos \delta' = \frac{\sin \delta_o (\delta_2 - \delta_o) - r_1 \cos \delta_o + r_2 \cos \delta_2}{r_2 - r_1} \qquad (87)$$

where

$$r_1 = \text{ratio } \frac{B_{max}}{A_{max}}$$

$$r_2 = \text{ratio } \frac{C_{max}}{A_{max}}$$

$$\delta_2 = \pi - \sin^{-1}\left(\frac{\sin \delta_o}{r_2}\right)$$

Also

$$T = \frac{\sin \delta_0}{r_1}$$

$$T_1 = \frac{T_0}{r_1}$$

$$\Delta T = \frac{1 - r_1}{r_1} \sin \delta_0$$

$$T_m = B_{max}$$

This equation has been expressed* in the form of three curves in Figs. 45, 46, and 47, whereby knowing r_1, r_2, and δ_o, δ' may be obtained directly. For example, from Fig. 45 for a given r_1 and δ_o, a value of A may be found; from Fig. 46 for a given r_2 and δ_o, a value B may be found. Then, knowing these, the angle δ' may be found from Fig. 47.

*By Mr. E. M. Hunter.

For a given set of conditions, the amount of power that can be carried through a fault with instantaneous switching and again with very slow† switching may be found directly.[1] For intermediate fault durations, the angle δ' may be determined from Figs. 45, 46, and 47, the time for the rotor travel from δ_o to δ' may then be determined from the curves in Figs. 34 to 43.

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†About 0.75 second.

Discussion

W. S. Peterson: In order to form a judgment of the general problem of stability, a great many portions of the problem are handled by solving a two-machine problem with generators at one end and synchronous machines, steam plants, synchronous condensers, or synchronous motors, at the receiving end. By the study of such a simple system, it is possible to form better judgments of what is happening. This brings up the point Mr. Summers mentioned of "boiling down" the system. He didn't mention it in his presentation of the paper, but in one of the appendices he refers to the method which was first presented by Miss Clarke, in which a portion of a system is represented by an equivalent machine at the end of the line. In a long transmission line there are the capacity effects of the line, a load on that line, both of which are shunt paths considered with relation to the synchronous machines at each end of the line.

At that time the device was originated of paralleling the impedance of the machine with the impedance of the shunt paths and the formulas devised by Miss Clarke are suitable to that purpose.

I have taken a little different attack on that problem, and suggest another method in which the machine is used with its original reactances, values of $W r^2$, and excitation voltages.

Assume there is a synchronous machine at one end of a transmission line, and another synchronous machine at the other end. Then when it comes to combining line capacitance and loads of any kind on the receiving bus, to form an equivalent machine, which is different from the machine being considered, it is preferable to bring into use the general circuit constants in which the loads and other shunt circuits are combined with the transmission line.

Evans, Sels, and Wagner, have shown ways of combining admittances and impedances, such as are found in connection with transmission circuits to form a new general circuit with constants, A, B, C, and D. Almost any sort of network between the two points can be represented by general circuit constants. The machines are then separated merely by a simple circuit expressed with these constants. It is possible to use the same power relationships, and formulas would be used in an ordinary transmission-line calculation, except that instead of the relationships being between the ends of the line, the relationships are expressed between the internal voltages of the synchronous machines. By this method it is possible to calculate the power angle diagrams, such as Mr. Summers has mentioned in his paper.

In general, it is this type of diagram, where power is plotted against angle, or torque against angle, which is the fundamental thing that is used in following the angular movements of the machines.

In using this method it is found that there is a considerable shift of the curve with respect to the axes, depending on the constants, loads, etc., assumed but I have suggested the method because it is the simplest way of handling the two-machine problem. It is exactly in line with the use of the driving-point impedance and the transfer impedance used in more complicated circuits.

In addition to that point I want to say that I think that one of the best aids to stability in addition to quick circuit breakers, is quick excitation. I should like to see the regulators and excitation systems developed to the point where the manufacturers would be absolutely sure that those devices can be depended upon. Otherwise, the stability of a line is too much decreased from the values we can obtain if we have absolutely good regulators. I think there should be much development in that particular branch of the work.

V. B. Wilfley: With reference to the section on the excitation systems, it would have been interesting to have had a more complete discussion of the exciter part of this system itself, that is, apart from the regulator.

To my mind, if you have a regulator which operates to close its contacts instantly on drop of positive sequence voltage, keeps them closed until the voltage is restored to normal, and has anti-hunting characteristics, you can ask no more of it. Then it is up to the excitation system proper. And to my mind most of the work on the quick-response excitation system must be done with reference to the exciter in conjunction with the generator field.

There seems to be considerable disagreement in the results obtained by factory tests as to just what is the best exciter response. This paper mentions 200 volts per second. That doesn't mean anything in itself unless it is considered with the rest of the system, but we have found in general that speeds of say 400 to 600 volts per second are in general more desirable and the expense involved in securing these speeds is very little, if any, more than that required to obtain 200 volts per second.

The matter of fast relaying and switching is certainly of importance and deserves emphasis.

I anticipate that there will be considerable improvement in circuit-breaker design and in system relaying within the next two or three years because that particular line has been lagging.

With regard to intermediate synchronous condensers and stability, I cannot agree with the author's statements. To my mind the intermediate synchronous condenser is to be largely instrumental in bringing about the transmission of large amounts of power over very long distances at high voltages.

It should be remembered that very fast relaying and breaker operation impose heavier duties on the system breakers. It is possible that you may go from one type of system trouble to another. That is, you may alleviate certain stability troubles and increase circuit-breaker troubles. That is something that should be kept in mind when making any changes on the system.

Mr. Peterson brought out the point that the manufacturing companies should arrive at a more solid basis regarding their guarantees on quick-response excitation systems. I think most engineers realize the difficulty involved. The benefit to be derived from quick-response excitation is very intangible and it is very hard to place an actual kilowatt value on it as compared with the added cost. Extensive studies on the systems involved are necessary in order to arrive at any idea as to what quick-response excitation will mean in the way of value. It is a matter of whether you can afford to stand certain outages or whether you want to spend some money and possibly eliminate them.

L. R. Gamble: On a recent development of the Chelan power site on the Washington Water Power system, an investigation was made of quick-response excitation. We found that it practically does us no good. We are praying for a circuit breaker that will do the job, a breaker that is extremely fast in operation under fault conditions.

Mabel Macferran: There appear to be two sides to the question of high-speed excitation. On the favorable side is the increase in synchronizing torque which results from the strengthening of the fields. On the unfavorable side is the virtual elimination of decrement in the short-circuit current. This increases the energy fed into the fault and so causes the rotors to slow down more suddenly, thus increasing the shock to the system. Such an effect will be especially marked on systems where faults contain appreciable resistance.

On the system of the company with which I am connected, it has often been observed that the synchronous condensers slow down markedly when a ground fault occurs. Apparently the rotors feed their inertial energy very rapidly into the fault, with the result that the speed sometimes drops as low as half normal value. This phenomenon suggests that one should proceed with some caution when applying high-speed excitation to condensers.

J. P. Jollyman: I agree with the conclusion of the authors that more speed is desirable in oil circuit breakers.

The question of system stability would be very largely solved if we could get trouble off the system in a very short time. A

very short time means under half a second and as much under as physically possible.

Excitation systems should have fairly high speed both for building up voltage and for lowering voltage. The first is needed when a decrease in transmission capacity occurs due to trouble or to the loss of a circuit. The second is needed when a generator or synchronous condenser is left on a long extra high-voltage line that has been suddenly disconnected from its load. Under these conditions the speed of a water-wheel-driven generator will increase from 10 per cent to 35 per cent which makes a quick decrease of excitation desirable, especially in the case of direct-connected exciters.

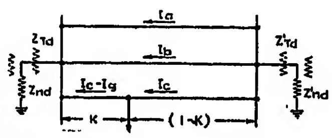

FIG. 1—APPARATUS CONNECTIONS IN SINGLE-LINE DIAGRAM FOR A HIGH-TENSION BUS AND TERMINAL APPARATUS

J. B. McClure and E. M. Hunter: (communicated after adjournment) Zero-phase sequence impedance of transmission lines has been given in Table II of the paper for several combinations of terminal connections including one, two, and four lines in parallel. To extend the usefulness of the paper and to make this table more complete, the zero-phase-sequence impedance of three transmission lines in parallel and connected terminal apparatus is presented here.

Letting,

$$Z_d = Z_{Td} + 3\,Z_{nd}$$
$$Z_d' = Z_{Td}' + 3\,Z_{nd}'$$
$$Z_a = Z_{Ta} + 3\,Z_{na} \qquad \text{etc.}$$

the general solution for the diagram shown on Fig. 3 is

$$Z_0 = -\frac{\begin{vmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{vmatrix}}{\begin{vmatrix} e & f & g \\ i & j & k \\ m & n & o \end{vmatrix}}$$

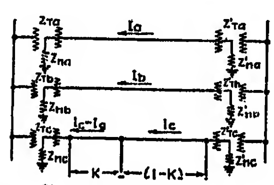

FIG. 2—APPARATUS CONNECTIONS IN SINGLE-LINE DIAGRAM FOR A LOW-TENSION BUS AND TERMINAL APPARATUS

where,

$$a = -[Z_d + K\,Z_{ac}]$$
$$b = -[Z_d + K\,Z_{bc}]$$
$$c = -[Z_d + K\,Z_{cc} + Z_3]$$
$$d = [Z_d + K\,Z_{cc} + Z_c]$$
$$e = [Z_a + Z_a' + Z_{aa} - Z_{ab}]$$
$$f = [Z_{ab} - Z_b - Z_b' - Z_{bb}]$$
$$g = [Z_{ac} - Z_{bc}]$$
$$h = [K\,Z_{bc} - K\,Z_{ac}]$$
$$i = [Z_{ab} - Z_{ac}]$$
$$j = [Z_b + Z_b' + Z_{bb} - Z_{bc}]$$
$$k = [Z_{bc} - Z_c - Z_c' - Z_{cc}]$$
$$l = [K\,Z_{cc} + Z_c - K\,Z_{bc}]$$
$$m = [Z_d + Z_a + Z_a' + Z_{aa}]$$
$$n = [Z_d + Z_d' + Z_{ab}]$$
$$o = [Z_d + Z_d' + Z_{ac}]$$
$$p = [Z_d - K\,Z_{ac}]$$

This general solution can be used to determine the zero-phase-sequence impedance of the following arrangements shown in Figs. 1 and 2.

(a) 3 circuits, high-tension bus, all switches closed; where $Z_a, Z_a' \ldots \ldots Z_c' = 0$

(b) 3 circuits, low-tension bus, all switches closed; where Z_d and $Z_d' = 0$

(c) 3 circuits, low-tension bus, any low-tension switches open. Same as (b).

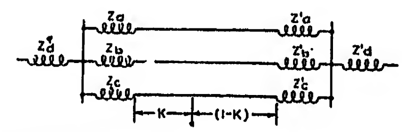

FIG. 3—SIMPLIFIED ZERO-PHASE-SEQUENCE IMPEDANCE DIAGRAM FOR FIG. 1

(d) 3 circuits alone (Z_0'), viewed from high-tension bus where $Z_a, Z_a' \ldots \ldots Z_c', K,$ and $Z_d' = 0$; Z_d is any arbitrary value assumed for convenience.

$$Z_0' = -\frac{Z_0\,Z_d}{Z_0 - Z_d}$$

Relay operation often gives cascading of breaker opening and hence, it is often desired to know the zero-phase-sequence impedance for the arrangement shown in Fig. 4.

The general equation for the zero-phase-sequence impedance of this set-up is

$$Z_0 = \frac{\begin{vmatrix} q & r & s \\ t & u & v \\ w & x & y \end{vmatrix}}{\begin{vmatrix} t & u \\ w & x \end{vmatrix}}$$

where,

$$q = [Z_d' + (1 - k)\,Z_{aa}]$$
$$r = [Z_d' + (1 - k)\,Z_{bc}]$$
$$s = [Z_d' + (1 - k)\,Z_{cc} + Z_c']$$

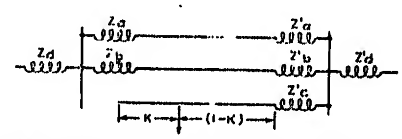

FIG. 4—SIMPLIFIED ZERO-PHASE-SEQUENCE IMPEDANCE DIAGRAM FOR FIG. 2

$$t = [Z_{aa} - Z_{ab} + Z_a + Z_a']$$
$$u = [Z_{ab} - Z_{bb} - Z_b - Z_b']$$
$$v = [(1 - k)\,(Z_{ac} - Z_{bc})]$$
$$w = [Z_d + Z_d' + Z_a + Z_a' + Z_{aa}]$$
$$x = [Z_d + Z_d' + Z_{ab}]$$
$$y = [Z_d' + (1 - k)\,Z_{ac}]$$

This general solution may be used to determine the zero-phase-sequence impedance of the following arrangements

(a) 3 circuits, high-tension bus, one high-tension switch open, where $Z_a, Z_a' \ldots Z_c' = 0$

(b) 3 circuits, low-tension bus, one high-tension switch open where Z_d and $Z_d' = 0$

I. H. Summers: Mr. Peterson's suggestion of using general circuit constants is a good one. It is probably a matter of preference which method to use and the method of circuit analysis with driving point and transfer impedances used in our paper is exactly equivalent.

Mr. Wilfley's remarks indicate that he believes that the

intermediate synchronous condenser is something to be mainly instrumental in bringing about the transmission of large blocks of power over very large distances. He does not give any data in support of this belief but we can refer to the discussion presented by Miss Macforran which indicates that in certain cases at least, synchronous condensers are somewhat detrimental to stability. The curves in Figs. 24 and 25 in our paper also fail to show any appreciable gain from the condensers under consideration. Further study and experience are needed on this point but it should be pointed out that at least the evidence seems to be lacking which would establish the great benefits which Mr. Wilfley claims for intermediate synchronous condensers when transient conditions are considered.

The question which Mr. Wilfley has raised in regard to the relative efficacy of different types of regulators is one which was rather thoroughly thrashed out after the St. Louis Regional Meeting in March 1928. The final outcome of the discussion which developed at that time was an agreement on the part of all of the parties who presented discussions, including several of Mr. Wilfley's associates, that the ability of regulators to improve the stability of synchronous apparatus can, in general, vary widely even though the conditions mentioned by Mr. Wilfley are fulfilled. That is, it was generally agreed that other factors can be important in regulator design besides those listed by Mr. Wilfley.

Unless Mr. Wilfley has some new thoughts or data which show that the results previously found were incorrect, it would seem unfortunate to raise this same question again.

It is gratifying to note the general agreement in regard to the benefits to be expected from quick switching. It would seem that breakers which will open the circuit in 0.2 second time are desirable and it is interesting to note that 230-kv. breakers which open the circuit in less than 0.2 second have actually been built and tested.

Series Synchronous Condensers
for Generation of Voltage Consumed by Line Inductance

BY THEODORE H. MORGAN*
Associate, A. I. E. E.

Synopsis.—The factors determining the power-carrying capacity of a transmission system are briefly discussed in this paper. The principal effects obtained by the operation of synchronous condensers used to compensate for the system consumption of lagging reactive kv-a. are pointed out. This method of compensation is contrasted with the direct method of supplying the reactive kv-a. to the line in the manner in which it is consumed, i. e., by the series method.

A plan for obtaining direct or series reactive kv-a. compensation by a method employing electric machinery is described. This includes a description of a method for producing the required voltage and inserting it into the system.

Some of the characteristics of operation and advantages to be gained by the use of the described method are given.

* * * * *

PRINCIPLES AND PRACTISE

A COMPLETE investigation of the transmission line power-limit problem shows that in the final analysis the limit of the amount of power which can be transmitted over a given system at a fixed maximum voltage and load power factor is determined by the total series inductive reactance of the system. The combined inductive reactance effects of the circuit, from the point of generation of the internal e. m. f. in the alternator to the point of voltage drop due to the e. m. f. of the load end machinery, determine the maximum amount of power that can be transmitted from the rotor of the generator to the rotors of the load machines.

The inductive reactive kv-a. of the load has its influence in limiting the maximum power which a system can transmit. An understanding of this principle, combined with the necessity of maintaining constant voltage at the load, has led to the practise of operating synchronous condensers at the load end of the line. These condensers may be considered as a source of inductive reactive kv-a. capable of compensating totally for load power factor, but only partially for line consumption of reactive kv-a. Such a method of compensation gives load end voltage control while increasing the system power limit. In fact, voltage control and reactive kv-a. compensation are interrelated, one action accompanying the other. The ultimate power limit is reached with the limit of compensation. The important fact related to synchronous condenser operation at the load end of the line is that complete compensation for line effects becomes impossible with increasing load, and the load and generator machinery finally fall out of step because of the inability of the system to transmit the load required of it.

About a year and a half ago, in an attempt to test out a new practise, an installation of series capacitors was placed in operation on a transmission line.[1] Such capacitors provide a method of series inductive compensation which is direct and inherently automatic. They produce a voltage across them which is opposite in phase angle to the voltage caused by the inductive reactance of the line. By proper choice of the capacitor size these two voltages may be made to entirely counteract each other, thus compensating for the inductive effects of the system. The line effects are completely eliminated and the amount of power which it is possible to transmit is very materially increased.

General Methods. It may be said that there are in general two methods by which reactive kv-a. may be supplied to a transmission system. First, it may be furnished indirectly by apparatus connected across the line in a manner similar to an ordinary load; or second, it may be added in a direct manner through apparatus connected in series relation to the line conductors. Each method gives compensating effects which are different in character and results obtained.

The first method changes the phase angle of the line current with respect to its voltage and in this way produces a line drop at such an angle that the load end voltage is held constant at a required value which may be equal to that of the generator end. This is shown in a simple case by the vector diagram of Fig. 1, in which the line charging current and resistance drop are omitted. With increase of line current, the angle between the generator-end voltage and the load current increases and the compensating reactive power supplied must increase with the load in order that the load voltage may be maintained. The maintenance of synchronism between generator and load is dependent entirely upon this principle when the phase angle between load current and generator-end voltage becomes large. This is because the power represented by these two quantities considered by themselves becomes diminishing under these conditions.

In the second method, the compensation is obtained by the addition of a series voltage to the system. This plan does not alter the line current, but the reactive kv-a. is produced by the inserted voltage acting with this current. The compensation is direct and the reactive kv-a. is supplied in the same manner that it is

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1. See Bibliography 2 and 3.

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consumed. Referring to Fig. 2, E_L, the voltage produced by line inductance is counteracted by the voltage E_C, equal to it and opposite in phase angle. In this case the line effects have been completely compensated for, and the load end voltage becomes identically equal in magnitude and phase to that of the generator end.

A New Method

The problem at its present status would seem to demand that all possibilities and options should again

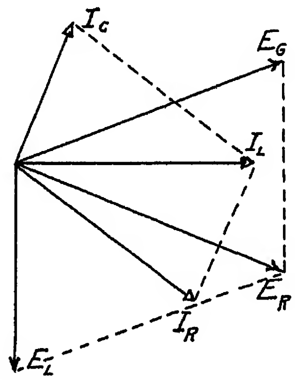

Fig. 1—Vector Diatram showing Compensation with Synchronous Condenser

E_G is generator end voltage
I_R is load current
I_C is correcting current
I_L is line current
E_L is voltage produced by line inductive reactance
E_R is load end voltage

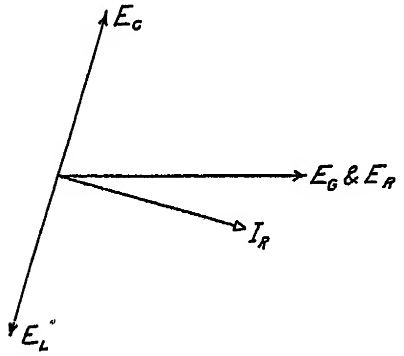

Fig. 2—Vector Diagram showing Direct Compensation

E_G and E_R are generator end and load end voltages
I_R is load current
E_L is voltage produced by line inductance
E_C is voltage supplied by correcting apparatus

be investigated. With the belief that the direct or second method is preferable to the one now commonly used, an attempt has been made to develop a plan by which the desired results may be obtained by the use of electrical machinery. It was realized that if a voltage identical both in magnitude and phase to that produced by series capacitors be generated and applied in series to the circuit, effects similar in general character to those realized by capacitors may be obtained. The following system of machine operation has been devised for this purpose.

Description. The general plan of arrangement is shown by the wiring diagram of Fig. 3. The reactive kv-a. required for compensation is supplied by a machine similar in construction to a synchronous condenser, which for want of a better name will be called the "inductive compensating generator." This machine is driven at synchronous speed by a synchronous motor, operated in the ordinary way from a bank of transformers connected across the line.

The voltage to be supplied to the line by the driven machine should be proportional to the line current since its purpose is to compensate for a voltage caused by this current flowing through the line inductive reactance. With the iron of the magnetic circuit of the machine below the point of saturation, this would require an exciting current which is at all times proportional to the alternating current of the line. This immediately suggests using the line current for machine

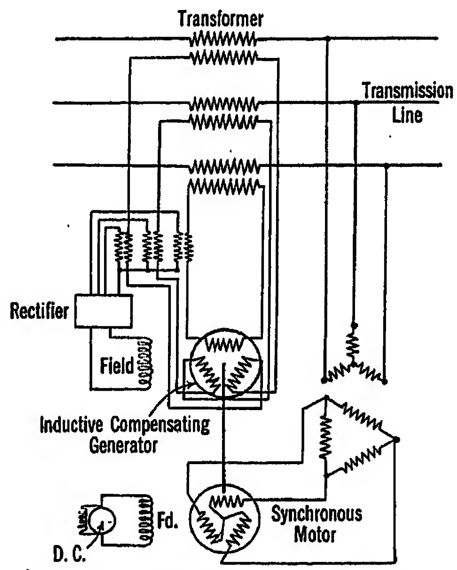

Fig. 3—Wiring Diagram of Arrangement of Apparatus

excitation purposes. This current may be passed through current transformers to obtain a suitable magnitude, then rectified with a polyphase mercury arc or other rectifier, and passed through the field circuit of the machine. Special current transformers with sufficient iron in the core would produce voltage impulses on sudden changes of line current, thus providing rapid response in machine excitation.

The requirements of frequency and magnitude having been met, there is the question of maintenance of proper phase relation for the compensating voltage. Due to its inherent characteristic, the driving synchronous motor would hold the rotor of the inductive compensating generator to an approximately constant phase position with respect to the line voltage. If it were possible to maintain constant power factor on the line, this is all that would be required, once the original setting of the angle between the two rotors had been correctly adjusted. However, since there is a

possibility of change of line power factor angle with change of load, it would seem that provision should be made to meet this contingency. The machine should normally operate with the voltage which it produces in leading quadrature relation to the current through it. By arranging the stator of either the driving motor or the inductive compensating generator so that it can be moved in such a way as to alter the relative phase angle between their armature windings, the required condition can be maintained. The real power output will always be zero and the stator position could be automatically controlled to produce this condition for all phase positions of the line current.

In cases where compensation is to be made on relatively low-voltage lines, the separate phase windings of the machine could be connected directly in series with the line wires. When used on high-voltage lines transformers would be necessary. These transformers would have their high-voltage windings placed in series with the transmission line wires and low-voltage windings connected to the machine phases. Such transformers would perform both series and potential duty and in addition, insulate the machine from the line voltage. They would act as series or current transformers in permitting passage of line current, the ampere-turns of both windings being equal. In stepping-up and introducing the machine voltage into the line they would be doing potential transformer duty.

With the inductive compensating generator being driven so that its generated e. m. f. is in leading quadrature to the current in its windings, there will be no torque or power developed by the machine. However, it will be operating in a condition of unstable equilibrium. By this is meant that on any relative displacement of the rotor and stator from the required position, a torque will be produced which will tend to still further increase the displacement. This torque will increase with the amount of the displacement up to the 90 electrical degree angle in either direction. The position of 180 electrical degrees from the required operating position is the stable one, and the rotor would seek this position if allowed to do so. In order to maintain the desired operation it is necessary that the driving motor be designed to produce more torque for small angles of displacement than that produced by the driven machine. Under normal operation the load on the driving motor would be very small as it would only be required to supply the rotation losses of the compensating machine. Thus for the driving machine, there would be required a relatively small motor with special characteristics.

Characteristics and Advantages. When this plan of compensation is applied to very long lines it might be desirable to insert a number of compensating units at intervals along the line, so that the supplied voltage would not be excessive at any single unit. This would also aid in keeping the line voltage more uniform throughout the entire length. For all cases of complete compensation, irrespective of the number or location of the units, the total reactive kv-a. supplied would be equal to the inductive reactive kv-a. consumed by the line if the line charging kv-a. be neglected. Also complete compensation by compounding the line inductance voltage would eliminate, in every case, its detrimental effects on voltage regulation and power-carrying capacity, leaving only the factor of line resistance.

The one operating benefit derived from line inductance is its effectiveness in limiting short-circuit currents. If the compensation were sufficiently complete to counteract all inductance effects of the line and transformers over the range of all possible currents, the short-circuit currents would be excessively high. The machine system of compensation, however, has the decided advantage that the magnetic circuit of the machine becomes saturated at certain currents and that its compensating ability is thus limited. As a result of this characteristic of the machine, it is possible to obtain full compensation up to a critical current, after which any appreciable increase in compensation becomes impossible. The effect desired is obtained by the inherent characteristic of the machine without any supplementary control. In this respect, compensation by machinery is far superior to that obtained with a series capacitor, which must be short-circuited on heavy currents with the resulting system disturbance upon its subsequent return to the circuit. With machine compensation, on the disappearance of the heavy line current, normal operation is restored by smooth action as the excitation on the machine is reduced.

In other respects it would seem that all the advantages claimed for series capacitor operation would apply to this method.

The inductive compensating generator is connected to the circuit in such a way that it will not supply its storage of rotational energy to a short circuit in the manner in which a synchronous condenser operates under such conditions.

CONCLUSION

The above described system of inductance compensation has been devised with the hope that it may in some small way point toward the solution of a vital problem in power transmission. No claim is made that the general plan is finally or completely worked out in all its details. On the basis of conformity to present practise, it will have no advocates. Because of its departure from methods now employed, many matters realized only through operating experience are as yet undetermined. However, granted that the general plan is fundamentally sound, its success must be inseparably linked with the ability to maintain complete, dependable, automatic machine control. In this regard it may be said that the rapid advance which is being made in the art of electrical controls is positive proof that this phase of the problem can be satisfactorily solved when the demand arises.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the faculty of the Electrical Engineering Department of Stanford University for many helpful suggestions, and particularly to Dr. Harris J. Ryan for his inimitable encouragement and assistance in the development of this plan.

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Discussion

J. A. Koontz: We know that in some cases the series capacitor has apparently been put into use with success on relatively low-voltage lines. It may be that some method as suggested by Professor Morgan might be worked out for high-voltage lines. It has been suggested that the synchronous condenser requires additional interrupting capacity in switchgear. By such a method some of this interrupting capacity would be eliminated. I do not believe that Professor Morgan thought the series generator, as proposed, would entirely eliminate the condenser as the condenser has a certain function of improving power factor, but it would take care of a portion of the additional condenser capacity that we utilize on our long lines for regulation purposes and as such might be of advantage if carefully worked out.

E. C. Starr: Would it be possible to apply this scheme on the low-voltage side of the transformers supplying the transmission line? If so the cost would be considerably less than if applied to the high-voltage side.

W. S. Peterson: There is one point I think we might bring out in this paper, and in presenting it I do not present it as a point of criticism. I merely offer it as a point of investigation for further improvement of the method.

It will be observed, from the suggested method of excitation involving the use of a series current transformer and a rectifier, that only the magnitude of the field current is controlled. There is no way of obtaining a change in the phase angle. This was brought out by Professor Morgan when he indicated the necessity for changing the rotor position for different power factors or different angles of load. During sudden or transient conditions there would be a very rapid change in the power-factor angle of the current. That is, the short-circuit current has a different power factor from the normal load current, and this sudden change will cause a considerable change in load on the motor, as brought out by Professor Morgan. These things will involve transient torque, which makes this problem the same complicated stability problem that we now have. This phase of it should be investigated in order to verify the workability of the system.

T. H. Morgan: I take pleasure in confirming the assumption made by Mr. Koontz that this new system has not been suggested as a complete substitute for the synchronous condenser in most cases. The synchronous condenser performs a duty in the correction of load power factor in a manner which it is very difficult to equal by any other method.

Mr. Starr's suggestion of operating the proposed correcting apparatus on the low-tension side of the system would be quite feasible and satisfactory in many cases. It appears to me that the answer to this question would depend to a very large extent upon the physical characteristics of the transmission system under consideration. It must be remembered that this is a series method, and as such, correction must be made at such a point that it will be in series with the total load on the line. On a long transmission line a number of correcting units might be placed at intervals along the line. Of course, in such a case it would be necessary to handle the high voltage on the transformer primary.

I believe the remarks of Mr. Peterson concerning difficulties under transient conditions are perfectly justified. Much investigation must be done before we can be in a position to state the exact and complete operation under transient conditions. The important information required in such an investigation is an accurate determination of the magnitude and phase angle of the line current under such conditions. The diversity of the many factors to be considered in this problem make it practically a separate one for each individual transmission system.

Recent Developments in Toll Telephone Service

BY W. H. HARRISON[1]

Associate, A. I. E. E.

Synopsis:—*This paper deals principally with the physical and technical phases of the development in recent years of "toll" telephone service in this country, with particular emphasis on the longer haul or "long distance" traffic. The very rapid growth in toll telephone business has required a rapid extension of toll plant including outside plant, buildings, and switchboard and other equipment. The most striking developments in the outside plant are very great growth in toll cable networks and the rapid extension of the carrier telephone systems. The factors involved in the relative use of these various types of plant are discussed. An outline is given of the advance planning and study necessary to insure that these annual programs are properly engineered so that, as closely as possible, they will effectively anticipate future requirements and extensions in a most suitable and practicable manner. The more important limitations affecting the design of toll plant from the standpoints of the efficiency, quality, speed, and length of telephone transmission and the specific treatments of each are generally discussed in the paper. These include such matters as the use of loading coils, vacuum tube repeaters, equalizers for attenuation and phase distortion, and means for reducing the effects of echoes and time lag or delay in the circuits. Mention is also made of modifications of the open wire plant to effect material reductions in crosstalk and to thereby permit a substantial increase in the use of carrier telephone facilities.*

The paper discusses the extension of toll service to include connection with the telephone networks in other countries including Canada, Mexico, Europe, Cuba, and South America.

* * * * *

THE term "toll" is applied broadly to telephone service between different localities as contrasted with "local" service which is, in general, within one municipality or center of population. From the early days of the telephone business the growth in toll service has always been rapid. This growth has, however, been particularly marked during the last few years.

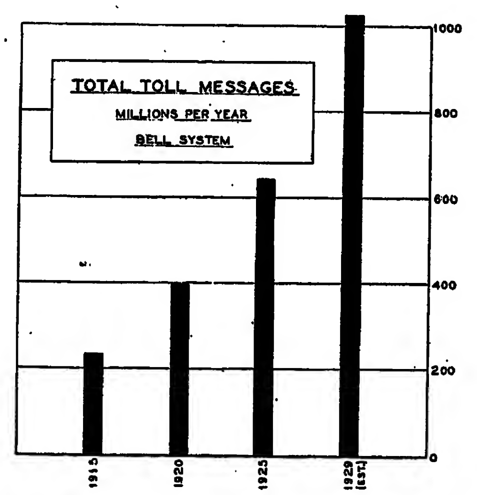

FIG. 1

It is the purpose of this paper to outline briefly some of the plant design and other engineering problems associated with the present rapid growth of this service.

MAGNITUDE OF GROWTH

The growth of toll telephone business is illustrated by Fig. 1, which shows the telephone toll messages per year in the Bell System for a number of years. This growth is perhaps more strikingly shown by Fig. 2 which shows in terms of cost the gross additions to toll plant per year for the last few years and the estimated expenditures for 1929. It is to be noted that not only is the per cent increase very rapid in comparison with that of past years, but it is expected to continue at a very rapid rate.

A remarkable feature of the increase in the toll business is the fact that the largest increases are being felt in the very long distance business, particularly on the transcontinental routes and the routes between the largest cities in the various parts of the country. Figs. 3 and 4, for example, illustrate respectively the growth in toll messages over a period of years between Chicago and New York, and between Chicago and Los Angeles,

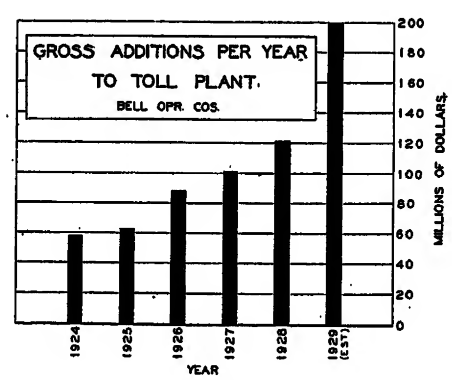

FIG. 2

which routes are typical examples of this growth. Fig. 5 shows the growth in messages for the combined toll business over the transcontinental routes between Chicago and New York and Los Angeles and San Francisco over the same period. It will be noted that while the toll business in the system as a whole has increased 34 per cent over the last 3 years, the toll messages between Chicago and New York have increased about 115 per cent, the toll messages between Chicago and Los Angeles 157 per cent, and the combined transcontinental business 226 per cent. These increases

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Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

29-150

in toll messages have required considerable enlargement of the size of the circuit groups between distant points and have contributed largely to the major construction problems in the design and layout of the plant.

The reasons for the recent rapid growth in the toll business are many. The growth has no doubt been influenced by the good level of general business in all parts of the country. There has also been an increasing

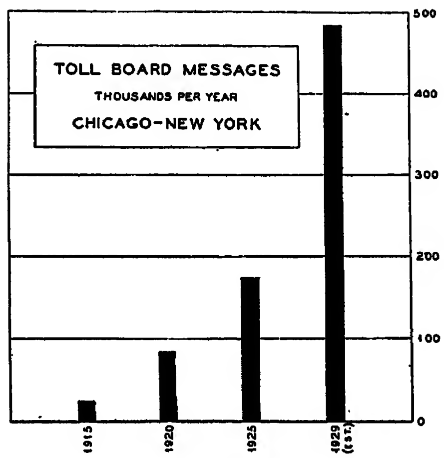


Fig. 3

public appreciation of the extent to which telephone toll service is of value in both business and social life and of the variety of uses to which it can be put. This is evidenced by the increasing number of by-product

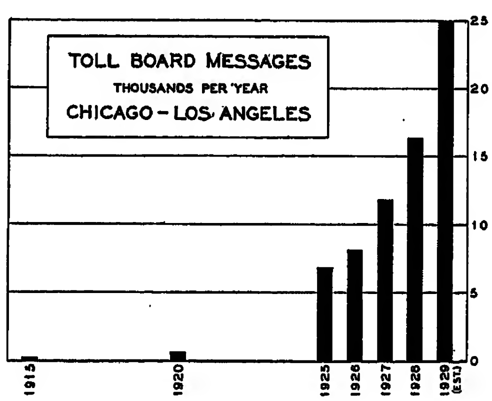


Fig. 4

uses and services which the toll user is constantly requiring. The continued development of economies in plant design, tending to limit increases in telephone rates to a much lower percentage than the general level of prices and which has made possible several recent rate reductions, is without doubt another important influence.

Considerable added stimulation to the growth of the toll business has undoubtedly resulted through improvements in the quality of the service given. Possibly the most important improvement in this respect is the increase in the speed of the service, that is, the decrease in the time which elapses between the placing of a call and its completion. This is shown in Fig. 6. The improvement is greater for the long distance calls than for the toll service as a whole, the average speed

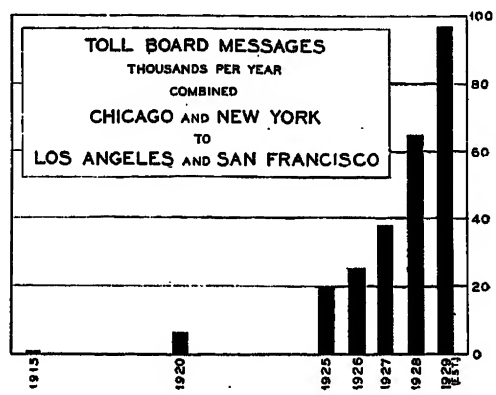


Fig. 5

for the toll board traffic being about 2½ minutes in 1928 as compared with almost 7 minutes in 1925.

The increase in the speed of handling toll service has been largely brought about by the introduction of improved operating practises and facilities which have permitted the use of simplified methods of operation similar to those employed for local business. An increasing amount of the shorter haul toll business is handled directly by the local operator who first answers the subscriber's call. The speed of the large part of the longer haul business which must be handled by toll board operators has been greatly increased by arrangements whereby the toll operator first receiving

Fig. 6—Average Speed of Toll Service

the call is enabled to do both the recording work and the switching necessary to complete the call. The result of the materially faster service has been that over 95 per cent of the total toll messages are completed or reported upon while the subscriber remains at the telephone, without requiring him to hang up and be called again.

Another important improvement in the quality of

service has been brought about both through large increases in the volume of sound delivered at the end of the toll circuits and by improvements in the design of circuits, resulting in the greater distinctness and naturalness of the messages. This has included the use of methods providing for the efficient transmission

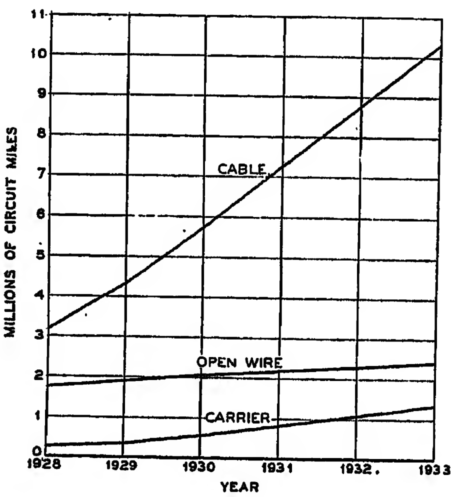


Fig. 7—Estimated Toll Circuit Miles in Plant Bell Operating Companies

of a much larger proportion of the component frequencies which make up speech. These improvements have largely reduced the percentage of messages in which the clearness of transmission is judged to be unsatisfactory, at the present time this being about 1 per cent for the total toll traffic.

Other improvements in service have led to greater freedom from the possibility of interruption of the service and to its improvement in other respects.

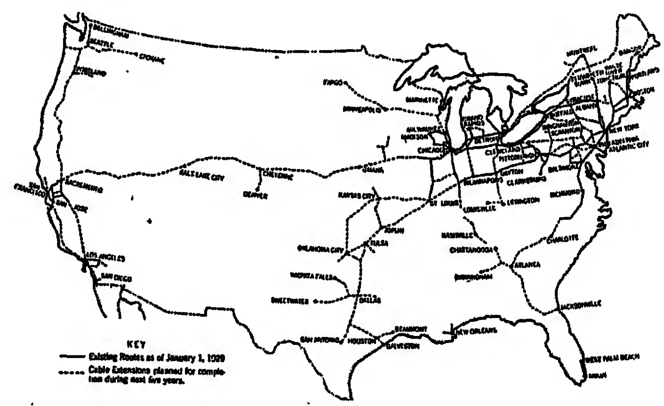


Fig. 8—Main Toll Cable Routes of the United States

While much remains to be done in the further perfection of the toll service, it is believed that material progress has been made in fitting it to the needs of the customer and this has, no doubt, been one of the outstanding reasons for the rapid growth.

Additions to Plants

The rapid growth in the toll business has required a great expansion of the toll plant and has been accompanied by material changes in the character of the plant and in the nature of the engineering problems. This expansion has been particularly marked in the case of the toll cable plant, additions to which have been experienced in practically all parts of the country. An interesting illustration of this expansion is given in Fig. 7, which shows the relative proportions of the three important types of toll plants at the end of 1928 and the estimated trend for this year and the immediate years following.

Toll Cables

It is interesting to note that of somewhat over six and a half million circuit miles in toll plant estimated for the end of this year, approximately four and a quarter million will be in toll cable. This percentage will be constantly increasing with the immediate following years. The extension of the toll cable

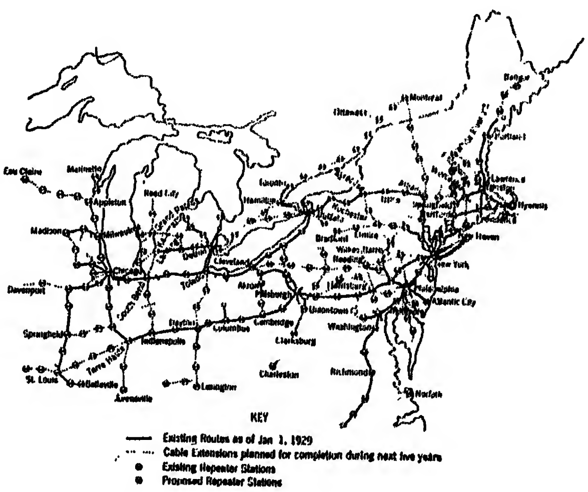


Fig. 9—Main Toll Cable Routes in Northeastern Section of United States and Canada

program over the next five-year period contemplates cable on a large proportion of all of the major toll routes of the country. The magnitude of the proposed cable networks is shown in Figs. 8 and 9. Fig. 8 illustrates the main toll cable routes of the United States and Canada. Fig. 9 shows the main cable routes and extensions in the northeastern area of the United States and Canada, the development in this area being considerably more dense than in any other section of the country. It will be seen that in accordance with these proposed five-year plans toll cable will extend entirely across the continent and up and down the length of both the Atlantic and Pacific coasts, as well as practically from Canada to Mexico in the central part of the country. With the completion of this large toll cable program, it is apparent that some of the toll messages will be routed within the five-year period through more than 4000 miles of cable.

The toll cable which will be installed in the Bell System this year will amount to nearly 5000 miles

This amount will be increased to between 6000 and 7000 miles for next year, and it is expected that the yearly additions will continue at that rate or even higher for the next few years thereafter. The estimated construction expenditures for the toll cable additions during 1929, including the supporting structures, conduit runs, and repeater and terminal equipments, will be in the order of about $100,000,000.

Types of Cable Construction

Both aerial and underground methods of toll cable construction are widely used in the Bell System, the

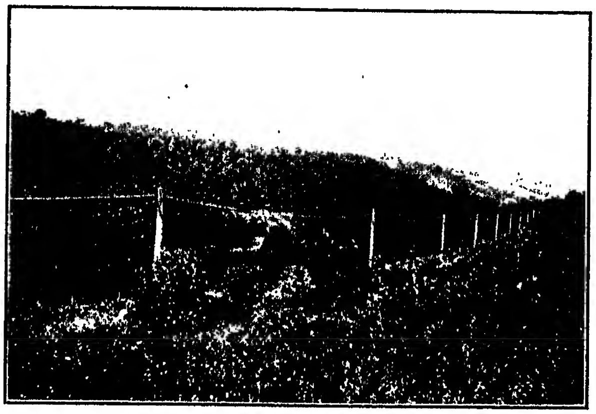


Fig. 10—Aerial Type of Toll Cable Construction

construction at the present time being about equally divided between these two general types. The greater part of the present longer haul toll cables are of the aerial type. In the aerial construction, the cable is suspended from a steel messenger strand supported on poles, as illustrated in Fig. 10. The aerial type of construction is, in general, limited to two cables per pole line and is, of course, used in the places where the growth is moderate.

The underground type of construction up to the present has consisted for the most part of cables drawn into multiple duct, usually of vitrified tile, although in certain sections of the country some use has been made of creosoted wood duct. The underground construction has naturally been employed in cities and metropolitan areas and in heavy and rapidly growing cable routes as between the cities of the Atlantic seaboard and between Chicago and New York, where the provision of facilities for placing a number of cables within a reasonable period of time is important. One of the first toll conduit and cable installations was made in 1908 between Chicago and Milwaukee.

During the past year trial installations have been made of two new types of underground construction designed to meet conditions where one or two cables will handle the requirements for a considerable number of years. One of these consists of a lead sheath cable pulled into a single fiber duct. In the other, a specially protected cable is buried directly in the ground without the use of ducts. The protection, known as tape armor, is applied over a lead covered cable of conventional design, the armoring consisting of coverings of impregnated paper, jute, and steel tapes which safeguard the lead sheath from soil corrosion and mechanical damage. In both of these types of construction, manholes are built only at loading points and thus about 90 per cent of the manholes employed in the more usual conduit structure are omitted.

The splices at the junctions of the sections of tape armored cable between the loading points are encased in split cast iron cases filled with asphaltum compound to prevent contact with the earth. Splices at similar locations in fiber duct installations are covered by large fiber sleeves. The placing of the tape armored type of cable is illustrated in Fig. 11. This type of buried construction appears to have advantages for some conditions where the rate of growth is not rapid. One interesting characteristic is reduced susceptiveness to inductive influences due to the shielding effect of the armor.

Both of these two types of construction have given satisfactory results in trial installations and it seems probable that they will find a considerable field of use in the Bell System.

Toll Cable Construction and Maintenance

The large annual additions to the toll cable plant necessitate the utmost care and precaution in planning and carrying out the construction and maintenance of this plant. The selection of the route for a toll cable is a matter of great importance, involving consideration not only of first cost and annual charges but freedom

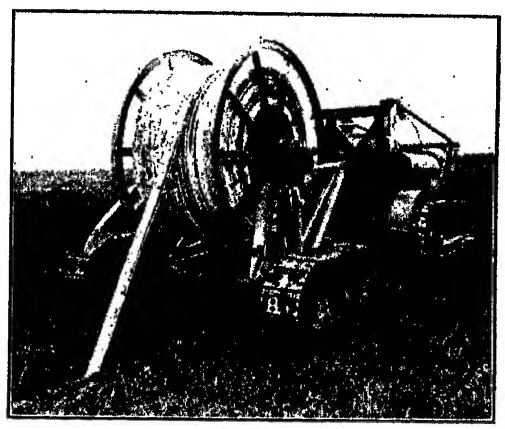


Fig. 11—Placing Tape Armored Type Toll Cable

from inductive disturbances, permanency of routes, accessibility, and good coordination with existing telephone plant. The assurance of relative freedom from interruptions to service of the toll cable plant requires also very careful consideration of suitable maintenance practises. Preventive measures are continually being developed and applied to the cable plant to aid this work. Interesting in this connection is the application of continuous gas pressure and associated alarm gages for the detection of cable sheath failures.

Other measures have been taken to minimize maintenance troubles on the toll cables. For example, much study has been given to the matter of securing the proper tension in the aerial cable suspension strand and a proper relation between the strand and cable tensions in order to obviate buckling of the cable due to temperature changes. Also, in placing cables in the usual multiple tile conduit before the cables enter the manholes, they are brought into a parallel formation, one

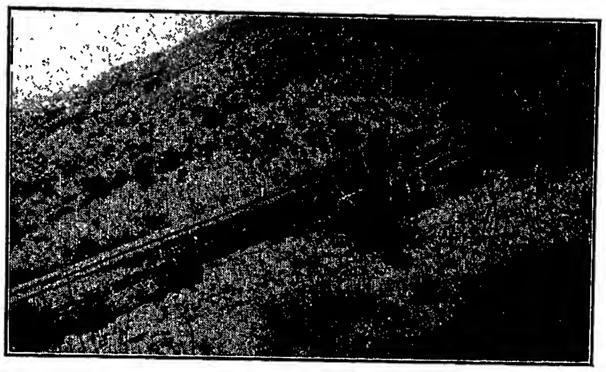


Fig. 12—Transporting Poles Up Steep Grades on Tractors and Trailers over Private Right-of-Way

above the other, by splaying the ducts at these points. By the use of this construction, the cables can be placed in the manholes free of bends.

There is also the necessity for very fast installation work in connection with the large toll projects, involving the desirability of making the fullest possible use of automotive and labor-saving equipment especially adapted for handling the pole, wire, cable, and conduit

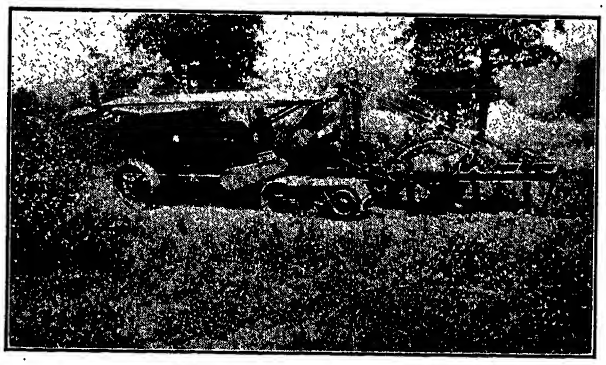


Fig. 13—Heavy Duty Trenching Machine

construction. This special automotive and construction apparatus includes such units as: four-wheel drive trucks, some of which are equipped with earth-boring machines; six-wheel heavy delivery trucks, several kinds of power derricks, trenching machines, back fillers, tampers, tractors, and several varieties of trailers. On private rights-of-way, as for instance over plowed fields, the ordinary wheel type trucks and trailers cannot be satisfactorily used so specially equipped caterpillar tractors and trailers with caterpillar tracks are employed. Some of the more important applications of labor-saving machinery in construction work are illustrated in Figs. 12, 13, and 14.

Aerial Wire and Carrier

In spite of the magnitude of the toll cable program, it is expected that it will be necessary, in order to meet the demand for additional toll circuit facilities, to string this year about 180,000 conductor miles of open-wire facilities and to install about 200,000 channel miles of carrier telephone facilities. The majority of this wire stringing will, of course, take place on existing open-wire lines not closely paralleled by toll cables. The increased use of carrier telephone facilities has materially favored the further extension of the open-wire along the long toll routes. The open-wire and carrier circuits now being designed are high grade facilities and their service characteristics and economies

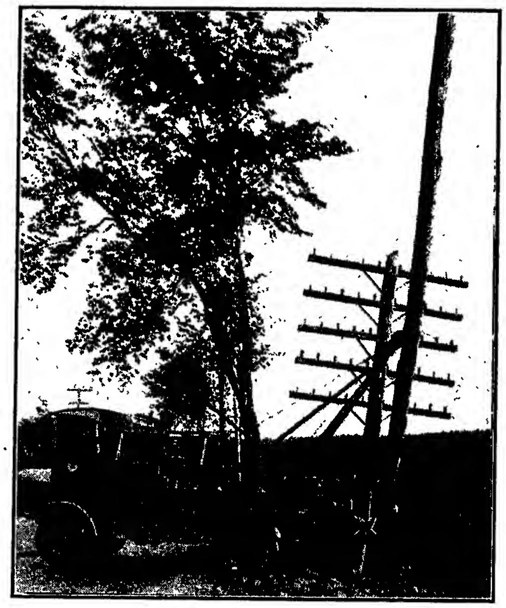
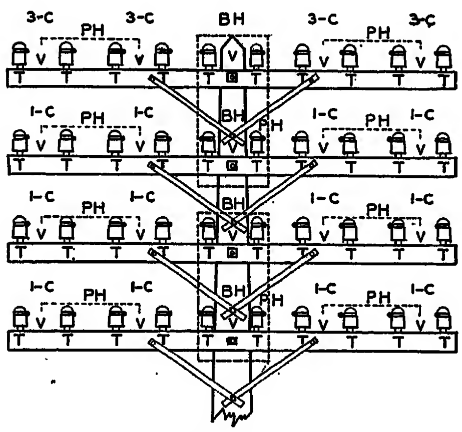


Fig. 14—Earth Boring Machine and Derrick on Four-Wheel Drive Truck

are such that a considerable portion of the open-wire and carrier facilities will be retained after they are paralleled by new toll cables.

Major problems presented by the open-wire and carrier construction have been those of crosstalk in the carrier circuits and noise in the very long voice-frequency circuits. In general, the magnitude of the crosstalk problems may be more fully appreciated when it is considered that carrier operation at present involves frequencies about twenty times higher than those important in causing crosstalk in voice operation and wavelengths about one-twentieth as long. Furthermore, the influence of surrounding wires, in parallel with the earth, gives rise to "second order effects" which become very marked within the carrier frequency range. Consequently, the inductive coupling per unit length between circuits is increased about in proportion

to the increase in frequency, a greater number of transpositions within each wavelength is required, the carrier facilities must be balanced with respect to second order effects as well as directly to each other, and the effects of irregularities in construction must be minimized to the greatest practicable extent. It has, therefore, been necessary to give careful consideration to transposition methods and wire arrangements which



LEGEND

SYMBOL	FACILITY	TOTAL CIRCUITS	
V	VOICE FREQUENCY-PHYSICAL	20	
PH	VOICE FREQUENCY-PHANTOM	10	
3-C	CARRIER SYSTEM FURNISHING 3 TELEPHONE CIRCUITS	12	
1-C	CARRIER SYSTEM FURNISHING 1 TELEPHONE CIRCUIT	12	
T	D-C TELEGRAPH	40	
BH	CARRIER TELEGRAPH (10 CHANNEL)	40	
	TOTAL TELEPHONE		54
	TOTAL TELEGRAPH		80

Fig. 15—Pole Line Configuration. Phantomed Construction

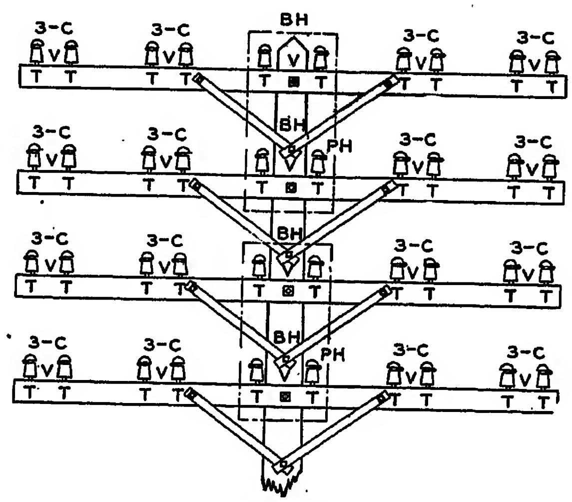
12-in. spacing between wires of non-pole pairs

would provide satisfactory crosstalk reductions and at the same time allow a maximum use of carrier facilities so that the large economies involved in superposing carrier telephone facilities on the open-wire plant may be obtained.

This has resulted in trying out in the plant an entirely new form of open-wire construction. The new method involves abandoning the phantoms on the open-wire pairs on which the carrier facilities are to be superposed, reducing the spacing between the wires of these pairs to 8 in., and widening the spacing between the wires of adjacent pairs to 16 in. The pairs to be used with carrier facilities are transposed in accordance with transposition systems which are especially designed to reduce adequately the coupling between the pairs at the higher carrier frequencies. The experience obtained to date with this type of open-wire construction, while not conclusive, has indicated very favorable crosstalk results. The reduction in the spacing of the open-wire pairs has also resulted in material improvements in the noise on the voice frequency circuits. Where a large proportion of the required circuits are for long haul use, that is to say in excess of about 100 miles, the new construction methods will make it possible to obtain 70 circuits on a 40-wire pole line, 22 voice frequency and 48 carrier circuits. With this arrangement, four carrier telephone systems can be employed per crossarm. The pole pair groups are not normally used for carrier telephone purposes and may therefore remain on a phantomed basis. Figs. 15 and 16 illustrate respectively the pole line configurations of the standard phantomed construction and the newer non-phantomed 8-in. spaced construction.

For routes involving a large proportion of short haul facilities, other transposition arrangements have been developed which make it possible to obtain economically 54 circuits on a 40-wire pole line. In this case the phantoms are retained and the wires are spaced on the normal 12-in. spacing owing to the fact that the carrier frequencies involved do not exceed about 10 kilocycles for the short haul facilities.

The field of use of carrier telephone facilities has been greatly increased with economies and improvements in two types of carrier telephone systems developed within the past few years. One type of system employs a frequency range of 5 to 30 kilocycles and provides three additional telephone channels normally used for long



LEGEND

SYMBOL	FACILITY	TOTAL CIRCUITS	
V	VOICE FREQUENCY-PHYSICAL	20	
PH	VOICE FREQUENCY-PHANTOM	2	
3-C	CARRIER TELEPHONF	48	
T	D-C TELEGRAPH	40	
BH	CARRIER TELEGRAPH (10 CHANNELS)	40	
	TOTAL TELEPHONE		70
	TOTAL TELEGRAPH		80

Fig. 16—Pole Line Configuration. Non-Phantomed Construction

8-in. spacing between wires of non-pole pairs

haul circuits from about 125 miles upward. Suitable intermediate repeaters are available for use with this system so as to greatly extend the range of its practical application. The longest systems of this type now in service are between Davenport, Iowa and Sacramento, California, a distance of almost 2150 miles.

The other system, employing a frequency range from about 4 to 10 kilocycles, provides a single additional telephone channel normally employed to provide

short haul facilities, ranging from about 75 to 125 miles. No intermediate repeaters are used with this system. Under special conditions this system can be extended to operate over approximately 200 miles, by the addition of extra terminal amplifier equipment.

Other considerations in the use of long haul carrier telephone systems have been those of reducing the transmission losses at carrier frequencies and thus extending the range of the system, the lessening in the spread of the transmission loss variations under varying weather conditions, and also, the maintenance of the over-all transmission equivalents of the carrier channels within satisfactory limits.

Investigation indicated that leakage effects are the predominating causes of transmission loss variations at carrier frequencies. This led to the development of improved glass insulators which materially reduce the attenuation at carrier frequencies and substantially limit the variations in attenuation between wet and dry weather conditions. Suitable transmission regulation of the over-all circuit has been realized through the use of pilot channels, by which the levels at all points in the carrier systems are maintained within established limits. Rectification at repeaters and terminals of transmitted high-frequency control currents permits the visual indication of the relative levels on calibrated meters. As changes in line equivalents affect both the pilot frequencies and the speech channels in a related manner and are indicated on the meters, compensating gain adjustments may be made.

The increased use of carrier facilities has tended toward bringing the relative costs of different gages of open-wire circuits more closely together, chiefly because of the wider repeater spans possible with the larger gage conductors. This is especially true of the 128-mil diameter open wire circuits which are, in general, not materially different in cost from the 104-mil circuits when completely equipped for voice frequency telephone, d-c. telegraph, and carrier telephone facilities. This has helped make economical the increased use of the larger 128-mil and 165-mil facilities throughout the open-wire plant, which is very advantageous in lessening the service interruptions due to wire breaks.

Toll Equipment Program

The rapid extension of the outside toll plant facilities has, of course, resulted in a very much increased toll equipment program. This has involved much engineering work in providing suitable switchboard and equipment arrangements, adequate building space, and improved methods of equipment assembly and office cabling. The extremely long distance circuits require numerous telephone repeaters, and the rapid expansion of the toll cable program, requiring repeater stations approximately every 50 miles, has materially increased the building and space requirements as well as the needs for additional repeaters, ringing and compositing apparatus, and adequate battery supply arrangements. As the present full size toll cables provide as many as 325 circuits, it is apparent that with many paralleling cables, building space frequently must be made available at one locality for several thousand telephone repeaters and associated apparatus. The following table, illustrating the increase in the use of telephone repeaters and carrier systems, shows the total number of telephone repeaters and carrier systems installed in the Bell System plant during 1925 and the estimated additions for the year 1930.

ESTIMATED ADDITIONS TO BELL SYSTEM PLANT

Year	Telephone repeaters	Carrier systems
1925	2,400	11
1930	36,000	400
Ratio	15	36

Simplified equipment arrangements have been developed which involve mounting apparatus on panels assembled on channel iron or I beam racks, thus bringing about substantial reductions in the space required as compared to the former types of mountings. The panel mounted arrangements have also considerably simplified the cabling arrangements between the various units of the toll circuit equipment required within a given office. Also, in order to simplify the layout and installation of the toll circuit equipment, arrangements have been developed whereby certain equipment is now shipped direct from the factory on completely assembled bays. Fig. 17 shows a bay of voice frequency telephone repeaters arranged in accordance with the latest methods of assembly and cabling. The simplification of the equipment arrangements is further shown in Fig. 18, which illustrates the complete assembly of two long haul carrier terminals with their associated testing apparatus, on standard bay arrangements.

The improved equipment arrangements have materially aided the repeater station building problem and floor plan layouts. The repeater station buildings which are being constructed throughout the country to house toll circuit equipment are, in general, fireproof buildings so designed that they may be extended vertically or laterally, depending upon the particular land conditions or other requirements involved. Fig. 19 shows a typical telephone repeater station on one of the major cable routes. This building now contains about 1000 repeaters. Telephone repeater station buildings are being constructed in several parts of the country which are designed to have an ultimate capacity of 10,000 repeaters.

Electrical Design Features

The development of very long toll telephone circuits has involved working out a succession of very interesting design features in order to obtain suitable electrical characteristics for the clear transmission of speech over these long circuits. These problems have, in general, been particularly great for very long toll cable circuits. They have been discussed in detail in a

number of papers presented before the Institute. A brief review of the general nature of some of these problems and the method of solution adopted for toll cable circuits will be sufficient here.

In the early extensions of toll cables, difficulty was experienced because of the much higher losses of energy for the high-frequency components of speech than for the low-frequency components due to the large variation in attenuation of the cable for currents of different frequencies. This difficulty was met by the use of "loading," by means of which the attenuation was made much more nearly constant over the band of frequencies most important for the transmission of speech. The loading also greatly increased the efficiency of cable

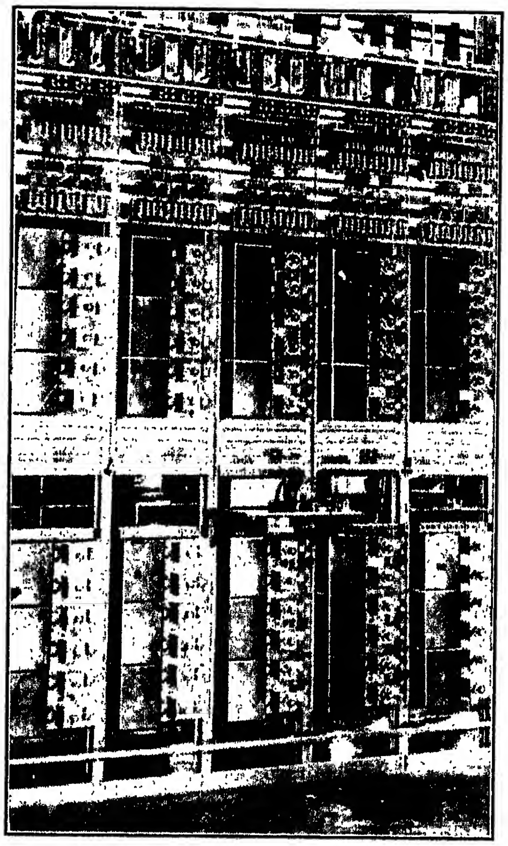


Fig. 17—Installation of Voice-Frequency Telephone Repeaters and Associated Apparatus

transmission by increasing the impedance of the circuit so that for a given power higher voltages and lower currents are used on a loaded circuit than on a circuit without loading. This made possible such cables as the early Chicago-Milwaukee cable, previously mentioned, and, by using as large gages of conductors as seemed practicable, provided satisfactory service through cables between New York and Washington and New York and Boston, distances of about 250 miles. These cables were completed in 1914.

Further extension of the range of cable transmission was limited by the difficulty of obtaining satisfactory over-all efficiency in cable on circuits of 200 or 300 miles in length. This difficulty was largely solved by the perfection of telephone repeaters, particularly those using vacuum tubes. In the design of long telephone

Fig. 18—Assembly of Long Haul Carrier Telephone System Terminals

circuits, even those in cable, it is now practicable to renew the energy of the telephone currents repeatedly without material distortion to a practically unlimited extent.

With the resulting extension of toll cable circuits to

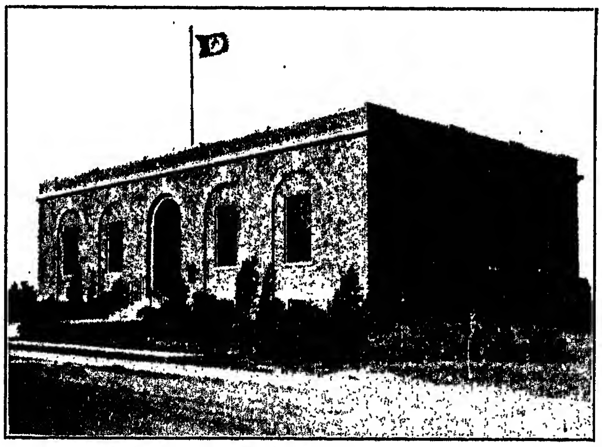


Fig. 19—Typical Repeater Station Building

relatively great distances, as between Chicago and New York, another phenomenon became of importance. At the ends of a telephone circuit the telephone currents are in part delivered to the terminal apparatus and in

part reflected back over the line due to the difference in the impedance of the line and the terminal apparatus. This effect also takes place in a minor degree at intermediate points in the line where discontinuities in electrical characteristics occur. When the time of transmission is very short, these reflected currents do not cause interference with speech unless they are relatively great in magnitude. When the time of transmission is appreciable, however, the reflected currents are heard in the telephone receivers both by the talker and by the listener as echoes. These echoes may have a serious effect in impairing the clearness of speech, the effect being progressively greater as the time lag of the echo current increases.

A first remedy for these effects was an increase in the velocity with which telephone currents were transmitted over the loaded cable circuits. This was done by a change in the design of the loading which also had other important benefits. With further increases in distance and in the efficiency of circuits, however, additional means were required to take care of these echo effects. This has been done by the development and use of means for suppressing the echoes by destroying the efficiency of the return path, that is, the transmission of speech currents in one direction over the circuit acts to prevent the transmission of echo currents in the opposite direction.

One important problem in the longer circuits has been the prevention of changes in efficiency with variations in the temperature of the circuit. The importance of this is illustrated by the fact that the energy loss in a Chicago-New York toll cable circuit may be as much as 10^9 times as great when the circuit is hot as when it is cold. The daily and even the hourly variations are sufficient to cause large variations in efficiency if not compensated. This compensation is done by the automatic change in the gain of amplifiers which is controlled by the resistance of pilot wires running through the cables and subjected to the same variations in temperature as the circuits used for message purposes.

In the longer cable circuits, the best system of loading which it has seemed practicable to employ, does not sufficiently eliminate variations in efficiency with frequency to permit the transmission of speech currents without serious distortion unless further means are provided. In such circuits, therefore, use is made of so-called "attenuation equalizers," inserted periodically along the circuit, to compensate for the variations in efficiency of the line and associated apparatus.

Another phenomenon which becomes of importance with increased length of circuit is the variation in the velocity of propagation over the circuit of different components of speech. The components of moderate frequency (about 1000 cycles) tend to arrive at the distant end first, those of higher and lower frequencies trailing in later. This produces an additional type of distortion. Some of this distortion can be minimized by improvements in the design of the apparatus. The use of corrective networks which insert in the circuit a distortion in velocity of transmission which compensates that caused by the cable circuit characteristics is also being studied to take care of this situation.

With all of these progressive difficulties removed, it appears, looking to the future, that the limit of transmission over telephone cable circuits may be influenced by the operation of another and still more fundamental factor, namely the time required for the transmission of electric currents over these very long circuits. With the development of toll cable networks covering this country and Europe and with the completion of telephone cables across the Atlantic, total distances of transmission over toll cable circuits as great as 10,000 miles will probably be involved in the future. The types of cable circuit now used for very long distances have a velocity of propagation of about 20,000 miles a second. The time lag in a 10,000-mile cable circuit would be about half a second for transmission in each direction. A delay of this magnitude would interfere with the ordinary methods of conversation involving frequent acknowledgment, interruption, and interchange of question and answer. Looking forward to improving such conditions, research work is now under way to determine the best means of providing cable circuits of still higher velocities.

International Connections

The toll system of the United States now has connection with telephones in 21 other countries. By this means the users of this service are offered connection with 65 per cent of all of the telephones in other countries of the world or 85 per cent of all the telephones in the world including those in this country. Additional extensions are made from time to time. These extensions to other countries involve many unusual plant arrangements and a brief mention of these is desirable.

Due to our very close relations with Canada, the Bell System connects with Canadian telephone systems at a large number of points. All of the larger cities and a large percentage of the smaller places are available for connection. In general, however, these connections involve no unusual problems, the ordinary types of construction standard in this country being extended in Canada where closely similar standards of construction are in use. Similarly, a connection made in 1927 to Mexico City and other important cities in Mexico by the extension of open wire toll lines involves no new technical features.

The connection of this country with Cuba was accomplished in 1921 by three submarine cables, of very unusual construction. These cables, 115 miles in length, cross the Florida Straits which have a maximum depth of about 6000 feet. Because of the great depth, the type of construction used for transoceanic telegraph cables was necessary for mechanical reasons and this made necessary a novel electrical design of the cables to provide adequate transmission efficiency. The

cables have proved very satisfactory and the availability of these circuits has resulted in the gradual development of a large telephone business between points in the United States and Cuba.

In 1927 the first commercial service was opened between the United States and Europe by a circuit from New York to London. This has since been supplemented by two additional circuits and other additional circuits now under construction and planned will raise this group to six by the end of 1932. The first circuit includes for the transatlantic link a long wave radio system transmitting from points near New York and London to receiving stations in the eastern central part of Scotland and northern part of Maine, respectively. The other two circuits are short wave radio circuits, both transmitting and receiving stations being near the New York and London terminals.

These circuits, both the long wave and short wave, are of pioneer character. The effort has been to obtain as good a degree of continuity of service as transmission conditions will permit and consistent with requirements for satisfactory commercial services. In working to obtain this result one is, of course, faced with the very large variations in efficiency of transmission under various conditions and also in the magnitude of the interfering atmospherics which tend to interfere with good reception.

With the long wave transmission (5000 meters), practically no degree of directivity of the transmitting antenna has been employed, although at the receiving antenna an improvement in the ratio of signal power to static power of about 400 to 1 is obtained by construction giving directive effects. In this connection, it might be noted that the northern location of both receiving stations is also an important factor in reducing noise. Relatively high powers are necessarily transmitted, the transmitting set power for long waves being about 200 kw. The power received by the receiving antenna is a small fraction of a micro-watt, sometimes being as small as 10^{-12} watt. It is interesting to note that this power is equivalent to that received from the North star on 10 sq. in. of the earth's surface.

With the short wave transmission using wavelengths between about 15 and 45 meters, it is possible to obtain a high degree of directivity of both transmitting and receiving antennas. The gains from the antennas used during the most important hours as compared with undirected transmission and reception represent equivalent power advantages of about 70 to 1 and 30 to 1, respectively. The transmitting powers used are somewhat lower than with the long wave, being about 15 kw. The short wave channels are, in general, less affected than the long wave by high atmospheric disturbances, but are much more affected at times of magnetic storms when large variations in the field strength of the signal at the receiving antenna often occur. Fortunately these two types of disturbances seldom appear at the same time and the two types of radio channel admirably supplement each other in the maintenance of uninterrupted service.

Work is now proceeding in the design of a transatlantic telephone cable which will provide a third type of circuit between New York and London. For this cable, transmission will probably be overland from New York to Nova Scotia, thence by submarine cable to Newfoundland, then by a second cable 1800 miles in length from Newfoundland to the Irish coast, and from there to London. This cable presents so great a departure from previous telephone circuits that extensive research and development are necessary to determine the most favorable methods of construction.

An additional international connection which is now being constructed is of interest, namely, a short wave radio telephone channel between New York and Buenos Aires, connecting with Montevideo.

Planning for the Future

In one or two places in this paper mention has been made of planning for the future by the intensive study of technical problems which might, if unsolved, limit future extension of the service. The scope of this paper does not permit even an outline of the numerous research projects which it is necessary to carry forward with a view to assuring continuity of uninterrupted progress in extension and improvement of toll service. This is, however, a factor of fundamental importance both in the steps which have already been taken and those which are anticipated in future years.

From the general engineering standpoint, the plans for the continued expenditure over a period of years of large amounts for permanent extension of toll plant, call for very careful attention to the fundamental planning and layout of that plant. This is particularly true in view of the large extension of toll cables and of underground toll cable conduit routes in which best engineering requires that initial construction be designed with a view to the future increase in circuit requirements for a relatively large number of years. This then is one of the important features of the engineering work of the Bell operating companies at the present time.

While fundamental plans for future development of toll plant must adequately provide for the plant extension in a given area, they must be closely coordinated with each other and with the plans for the country as a whole, particularly because of the importance of the large groups of long through toll circuits. As one element in facilitating this planning, there has recently been developed for the country a general basic routing plan designed to insure the highest practicable standards of service as to speed, accuracy, and transmission with maximum economical concentration of circuits on important routes. This plan will serve to limit the amount of switching required for handling toll calls between remote points.

Conclusion

In the above discussion, I have endeavored primarily to give you in brief outline a general picture of the engineering aspects of the situation surrounding the recent development of the toll service side of the telephone business and to touch upon some of the technical matters which have been important factors in the progress of the toll expansion program. Detailed discussions and analyses of many of the more interesting of these problems have been presented in recent papers before this Institute, or have appeared in various of the technical publications For the convenience of those who may be interested in a more detailed consideration of these matters, a bibliography of a selected list of these papers is attached hereto.

In conclusion, I might add that those of us who are closely interested in the advancement and improvement of the toll phase of the telephone business look forward to a continued rapid development of that part of the communication art with an increasingly complex and varied engineering technique.

Acknowledgment

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Discussion

H. A. Harris: When planning large annual additions to toll plant it is usually necessary to consider many related matters bearing on future toll service and operating methods and to know the reaction of the proposed plans upon the economical use of the balance of the plant. A plan generally known as the "Toll Fundamental Plan," considers such matters and develops all the necessary facts for use as a guide in all current toll plant construction.

A well prepared toll fundamental plan indicates, for some future period (usually some 15 or 20 years in advance), the estimated amount of toll traffic that will be interchanged and the most effective toll operating methods to be used in handling this traffic between any two points, the toll centering arrangement which will include those points and the estimated number and arrangement of circuits to be required. The plan also shows the most economical type of plant for providing the estimated toll facilities, *i. e.*, open wire, cable, or carrier system to meet service requirements in each route.

In brief, these long range plans are a safeguard against any danger of providing facilities incorrectly, either in amount or direction, and also a safeguard against the adoption or continuation of any plant arrangement or operating method which, although it may seem reasonable at the present time, might later, as the system grows, prove uneconomical.

The foundation on which all this advance planning is built is, of course, the forecast of calls per telephone or toll usage. Unlike local traffic this usage does not remain constant from time to time but varies a great deal with business activities and is sometimes subject to other influences so that in the advance planning of toll plant it is necessary to exercise sound judgment and to apply frequent reviews in forecasting the probable future trend of service demands and characteristics. Upon the results of these studies and forecasts, operating plans are adopted and construction details determined. This portion of advance planning work is therefore the key and a highly important part of toll telephone engineering.

W. W. Walters: Mr. Harrison, in describing the expansion of the toll plant, mentioned its changing physical character and the changing nature of the engineering problems. In this connection it may be of interest to compare some features of a specific toll cable project of 1915 with those of a paralleling project of today.

The original Great Lakes-McHenry cable extending 26 mi. across Northeastern Illinois was a pioneer achievement in the quadded toll cable field. It was installed in 1915, replacing an open wire plant suffering from the familiar sleet storm effects and was confidently expected to care for all toll growth in that region for a 20-year period. Although serving an agricultural and summer resort region wherein growth was expected to be and has been relatively slow, it was nevertheless necessary to provide some measure of relief in 1927. This was accomplished by rerouting the longer haul circuits to a relief cable installed in another location. The results proved to be temporary, however, since the rapid growth in requirements during the past three

years necessitates another relief cable on the original route by 1930.

The engineer of the relief project, although the beneficiary of 15 additional years of experience in the art of forecasting, is not so confident as his predecessors when he indicates that the Great Lakes-McHenry relief cable should care for all requirements in the path until 1940. He has learned for one thing that the projection of accumulated past performance records alone cannot possibly reflect the changing conditions of the future. His risks are smaller, however, since he is, in general, engineering for shorter periods than his predecessors did.

The original Great Lakes-McHenry cable contained 13-gage quads and 16-gage pairs with a maximum capacity of 96 circuits. Since the introduction of telephone repeaters, the same or better transmission performance can be secured economically with smaller gages, and 13-gage copper is no longer employed in toll cables. The 1930 relief cable will, therefore, be predominantly 19-gage with a capacity of 378 two-wire circuits, yet having approximately the same copper content as the original cable. In addition the new cable facilities will be segregated for four-wire operation in case circuits of this type may be required at some future date. The cable will also contain special high grade pairs suitable for the transmission of program material. The telephone circuits can furthermore be adapted to provide 200 or more superimposed telegraph channels without interference to the regular telephone service. These additional features were almost entirely absent in the original cable.

The old cable was loaded at 8700-ft. intervals and transmitted a rather narrow frequency band. The new cable will be loaded at 6000-ft. intervals and also balanced at 3000-ft. intervals to take advantage of still shorter spacings which may be introduced in the future. Rigid limits will be observed in securing a regular spacing of the loaders, an essential requirement to good repeater operation but of less importance in 1915 when repeater applications were still undergoing development trials.

When the original cable was installed the volume and quality of transmission provided was probably somewhat poorer than that given by the open wire circuits which it replaced. These impairments, however, were compensated for largely by the comparative freedom from noise and crosstalk which the cable circuits afforded so that the net result, coupled with the increased reliability of service, was probably of sufficient excellence to satisfy the standards of 1915. Transmission designs were largely directed towards providing suitable performance between terminal points connected with direct circuits, there being at the time no particular demand for long-haul, built-up connections requiring the switching of two or more circuits together in tandem. The relief cable of 1930, together with its associated facilities, will provide circuits having marked improvements in both the quality and volume of transmission and should perform satisfactorily in any type of long-distance connection which may be needed, a requirement and an accomplishment almost unforeseen in 1915.

Burke Smith: Mr. Harrison mentioned the transatlantic telephone circuit and referred to the increase in circuits from 1927 to the present time. I believe it was opened with one circuit and at the present time there are three, and in 1932 I think six are expected. I am just wondering what the traffic conditions are on the transatlantic circuits. I have in mind the recent stock market flurry. What were the traffic conditions during that period?

W. H. Harrison: When the transatlantic circuit was first opened in 1927 the average number of daily messages was about 7. In 1928 this had increased to about 30 a day and for this year the average is a little above 50.

During the stock market activity at the end of October, slightly more than 100 calls a day were handled during the last three or four days of the month. For one of these days there were close to 200 calls offered, and we were able to complete only about 140 of them. Another interesting feature of the transatlantic business is the fact that the calls offered at the two ends are nearly equal, 50 to 55 per cent being offered at this end and 45 to 50 per cent at the other end. About 55 per cent of the total calls are to or from Great Britain, about 30 per cent terminate in France, and about 8 per cent in Germany, with the remaining calls scattered among the other countries in Europe.

The Chicago Long Distance Toll Board

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Synopsis.—The long distance telephone office serves to provide a concentration point for intercity telephone communication from a group of local exchanges and its size will depend largely upon the number of stations served by the local offices.

The Chicago Toll office, which serves 1,200,000 stations, has recently been largely replaced with new equipment. This equipment, together with correlated improvements in handling toll service at Chicago, is described in this paper.

The work of the toll operator in handling toll calls with the new equipment is compared with the former method and it is this change in operating practise which constitutes a major improvement in long distance service.

The paper also includes a description of the toll lines entering Chicago with their equipment arrangements including telephone repeaters and the power plants required to operate this equipment and that associated with the switchboards.

The addendum describes the purpose of the auxiliary and special switchboards which are required only in large installations such as Chicago.

* * * * *

THE growth of the long distance telephone traffic along with many improvements in service have recently brought about certain significant changes in operating practise. The long distance toll user may now, in the majority of instances, remain at his instrument during the complete progress of the call. This, together with a reduction in the time interval between the placing of the call and the answer of the distant station from a former average of six to a present average of less than three minutes, brings long distance and local service very closely together, from the standpoint of simplicity and convenience to the user.

The accomplishment of this change required careful planning and supervision throughout the Bell System but did not, except in the larger cities, involve relatively large or expensive equipment rearrangements. Conditions were such at Chicago, however, that the change in practise, together with preparations in connection with the continuing toll volume increases, made it advisable to replace part and remodel the remainder of the existing toll switchboard equipment.

Such action at so large a center constituted a major problem in telephone engineering. It also included various operating and equipment features which, being of the most recent type available, make the new office one of the most completely advanced within the system. This paper describes the actions taken in the new installation and the general operating and toll circuit layout, and prefaces this description with a brief outline of the general relationship of the toll plant to that of the system as a whole.

The General Telephone System

The telephone system is composed of local exchanges with direct completion of calls between stations within the local exchange boundaries and with switched toll line completion of calls between exchanges. It is unified as to plant standards and methods of operation, so that its whole system is as accessible to any one station as to any other, regardless of sizes of exchanges or their remoteness from each other.

At each local wire center the lines or loops from all subscribers' stations are brought to one central office switchboard for purposes of their direct interconnection. If, as in large metropolitan areas, this concentration involves too extensive a wire haul, the geographical group is split up into economic sub-areas with sub-wire centers connected together by direct local trunks.

This same general arrangement is supplied for intercity or toll connections. Adjacent and neighborhood communities are connected by direct toll lines, and more widely separated cities receive their toll service through selected toll centers or switching points strategically located throughout the system's territory.

Each toll office is a focus for all originating and terminating toll business from and to its tributary local offices, and the effect of this toll centering is to concentrate toll traffic into units large enough to permit the most economical balance between the costs of the switching operations and the costs of the toll line plant.

The Chicago toll office, at one of the great regional centers of this country, is a key switching point within the country wide network of toll lines and directly serves the 32 local wire centers with 102 central offices and the 5 suburban wire centers, which together form the Chicago Metropolitan Area. Within this area some 1,200,000 stations will have originated approximately 7,300,000 calls via this toll board during the year 1929, in addition to some 44,500,000 calls which will have been handled by the Chicago local offices themselves to nearby toll points.

The Work of the Toll Operator

Under the toll centering arrangement the local and tributary offices are connected with their toll office by groups of recording and toll switching trunks. Prior to the change in the method of toll operation, already referred to, the recording trunks terminated on separate recording positions and a special recording operator worked only to secure the necessary details of the call from the calling subscriber. She then released the subscriber's line and passed a ticket memorandum of

1. Illinois Bell Telephone Co., Chicago, Ill.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., December 2-4, 1929.

29-149

the call to separate completing operators at an outgoing switchboard line. These operators re-secured the subscriber over toll switching trunks, reached the distant station over the toll lines and then established the connection and timed the call.

With the change in method the recording and completing or "line" operators' functions have been combined and located entirely upon the outgoing switchboard. To indicate this method of combined line and recording work, an expression, "CLR" has been coined, telephonically, and will be used as such throughout the paper.

Since provision must be made for incoming as well as outgoing traffic and for toll center to toll center switching, we will generally find that the larger toll switchboards are divided into three groups or lines for CLR or originating business, for "inward" or terminating business, and for "through" or switched business. As in Chicago, there are also apt to be various additional special groups to meet the functional requirements of such large toll line and toll volume concentrations as are there encountered.

In handling a CLR call from a manual subscriber the CLR operator makes a permanent ticket record of the call details and then, without releasing the subscriber from the recording trunk, rings out over an idle toll line to the distant operator, using a separate pair of cords, and asks for the called station. While waiting for the called station's answer, she secures the calling subscriber's line over a toll switching trunk, using the same pair of cords used to ring out over the toll line, and releases the recording trunk. Upon receipt of an answer by the called station, she stamps the time of day in hours, minutes, and seconds with a calculagraph stamp on the ticket, and upon receipt of final disconnect signals stamps the time when conversation ended. Billing is finally made upon the basis of charges applied to the elapsed time indicated on the ticket.

One of the chief savings in time to the subscriber under this procedure, as compared to the former separate recording and completing operation, is the saving in ticket distribution time between the two sets of operators. As can also be seen, greater speed is possible when the called station number is known than when it must be looked for in a directory.

Reciprocal work must be done at the terminating end of each originating connection by an inward operator who answers the incoming toll line signal and reaches and rings the station called for by the originating toll operator. In handling switched calls, the intermediate or through operator deals only with the distant toll operators who reach each other over toll lines routed via the intermediate toll center board, these lines being connected together at the through positions by the through operator.

Toll calls are handled on the basis of connection with a particular person (a person to person call) or with someone who may answer at the called station, (a station to station call). Either class of service is available to the subscriber whether he calls by name or by number. When anyone will suffice the call is necessarily completed upon the answer of the called station and will be delayed only by a "don't answer" or "busy" condition at the called station, or by toll circuit congestion. On a particular person call, the inability to immediately reach the one person desired at the telephone specified may cause delay in addition to the above causes.

The various operations required to secure completions under conditions of postponement involve many different methods and routines which are rather technical in their applications and require additional distributions of the ticket memoranda and various specializations of work. All are designed to conserve whatever necessary time intervals are involved and to insure the definite completion of the call in the manner asked for.

The Chicago Toll Board

An example of the specialization required is given in the following tabulation of the Chicago Toll Board positions:

(a) CLR	301	(f) Directory	44
(b) Non Method	233	(g) Routing	16
(c) Utility	78	(h) Delay Quoting	4
(d) Inward	89	(i) Traffic Trouble	4
(e) Through	113	(j) Office "B"	6
Total General	814	Total Miscellaneous	74

(k) Ticket Distributing	24
(l) Ticket Filing	24
(m) Service Supervisor	16
(n) Service Observing	20
(o) Monitor Tap	1
Total Auxiliary	85
Toll Tandem	16

These switchboards, which are grouped upon six floors of one building centrally located in the downtown business district of Chicago and designed for an initial service of some 32,000 toll board calls per day, are arranged to accommodate the following line and trunk equipments:

1. Toll line to all points	2700
2. Switching trunks to local offices	3800
3. Recording trunks from local offices	850
4. Miscellaneous interboard trunks	1200
Total network	8550

Each of the switchboard position and line group arrangements has specific functions which are somewhat abstract for the scope of this paper, and which can be only briefly summarized as in the addendum. Certain controlling factors should be pointed out here, however, as follows:

Subgrouping and Tandem Arrangements. The capacity of the face equipment of the CLR boards is insufficient to accommodate the whole of the recording and switching trunks on a workable basis. The CLR group has,

therefore, been subgrouped into four units, each of which serves a specific subdivision of the Chicago local exchange.

In spite of the various measures taken to reduce the space requirements for face equipment at the CLR position, it did not appear practicable to provide appearances for all of the toll lines at each CLR position. A trunking plan is therefore necessary which introduces a toll line "switching" or "tandem" board within the office itself and the CLR operators thus reach a majority of the toll lines needed by them on a trunking basis. One of the lines of CLR positions is shown in Fig. 1. This line consists of 65 positions.

Directory and Routing Arrangements. More than 2100 directories, covering 350 metropolitan areas and communities extending from coast to coast, are indexed and filed on a state basis at a line of directory switchboards. The CLR or other service operators communicate with the directory operators by trunks, without

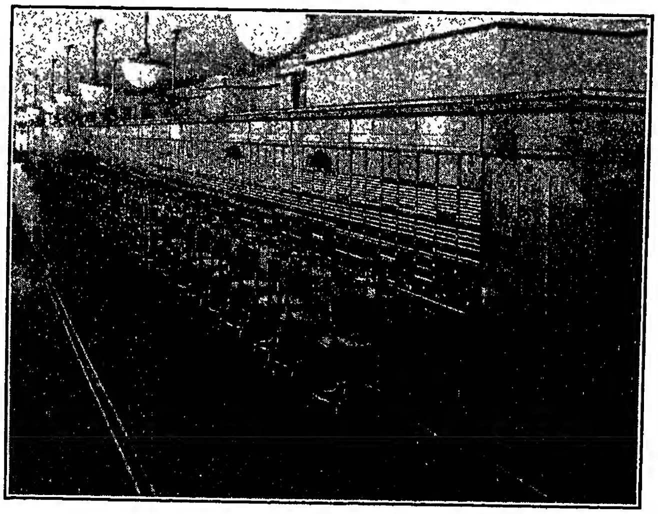

Fig. 1—A Line of CLR (Combined Line and Recording) Switchboard

delay for such telephone number information as cannot be furnished by the subscriber himself. A picture of the directory positions is shown in Fig. 2.

At certain other positions, other operators specialize in quoting the routes to points not obtainable on a direct connection basis. These routings are based on frequent and thorough traffic engineering studies of the entire toll network throughout the territory involved.

Pneumatic Tube System. Because of the location of the various switchboards on several floors, it is necessary that means for rapidly transmitting tickets from one location to another be provided. An exhaust blower, a system of flat brass tubes and ticket distributing positions comprise a pneumatic tube system for this purpose. With one end folded to form a pocket for the tube air currents, the tickets are inserted at any position and delivered to control or distributing positions where they are checked and routed to their proper destination. Either roller or hand receiving valves permit ticket egress at the terminal points. There are two distributing desks in service and one of these is shown in Fig. 3. The wooden "trimming" panels have been removed to show the tubes.

Engineering Problems Involved. Consideration of the situation at the Chicago center had established the fact

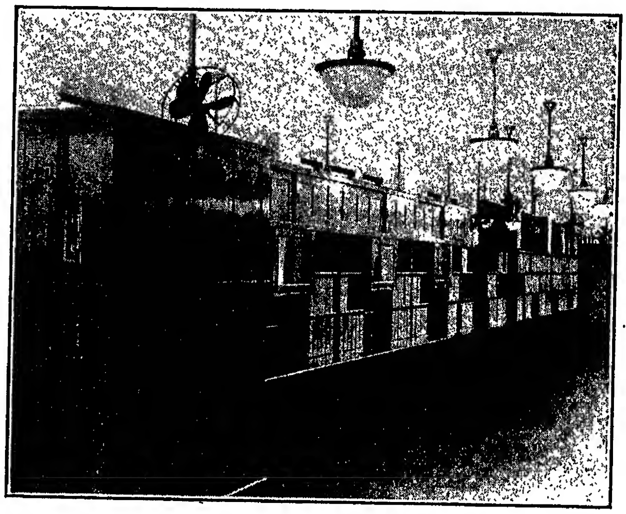

Fig. 2—The Directory Positions

that the increasing toll volume growths would require equipment floor space in excess of that which could be made available without additional building operations. In 1926 it appeared that the rather appreciable equipment additions required for growth and those required to permit of change to CLR operations would tend to advance the new building work and would

Fig. 3—One of the Ticket Distributing Desks

require new switchboard line arrangements to permit this to be readily carried out.

At this same time new and improved toll switchboards of a more efficient type were being made available and it was desirable to utilize this type even though these could not be used in conjunction with the existing type boards without appreciable modifications within the

latter. These various factors after proper engineering cost study and management consideration combined to indicate that the dismantling losses upon part of the existing switchboards and the new money requirements could be justified on the basis of improved efficiencies in service and over-all economies in providing for future growth. Since a clear path for future building work could also be secured it was decided that the old switchboard was to be largely replaced.

The general building conditions were such that the new switchboards, when completed, would be to a large extent occupying the old switchboard space, and yet service must be kept upon a continuous basis upon the old boards. This was met by the invention of special "applique" circuits which were attachable to the old board circuits to make them workable with the new board circuits. By this means, old and new were placed side by side as installation work proceeded and the service was continuous and yet made ready for cut-over.

The problem in connection with the congested face equipment space of the CLR boards which, as already referred to, resulted in a toll tandem board arrangement brought into service an entirely new development designed especially for metropolitan CLR offices. This includes idle indicating lamps so arranged that only the first idle circuit to the left of the group or subgroup of toll lines is indicated, and of overflow jacks so arranged that one request for each busy toll circuit group received from the CLR operators may be held. When a circuit becomes available, the overflow jack functions to signal the operator who has requested the circuit.

It was felt also that all other equipment or operating improvements which were available should be included in this one big project. Under this head, came the terminal repeater pad arrangement to eliminate cord circuit repeaters and this was added to the already complicated plans for Chicago.

Under normal conditions, each step in the development of new equipment and operating methods is worked out in a preliminary manner and given a complete work-out on a trial basis. If satisfactory, requirements are then worked out on the basis of manufacturing production and given to the field. Field engineering considers these in connection with existing and potential conditions and includes them in cost and other studies which result in detailed specifications. The manufacturing company then carries out its detailed engineering and manufacture in accordance, ships the material and installs it.

The general plans for the Chicago project had taken nearly a year for their complete preparation and decision. It appeared that a requirement for completion by March of 1929 would be necessary. The difference in effort between the two years available for completion and the greater period normally involved in the cycle, as above referred to, needed to be carefully measured since development, engineering, manufacturing, installation, and operation, together with space rearrangements would need to be carried out almost simultaneously. This was reviewed and discussed from the system's standpoint and it was determined that with the necessary planning and coordinated effort the objective could be met. This was successfully accomplished by the date set with complete satisfaction.

The functioning of the general development and research departments and the laboratories of the Bell System, together with its ability to summon all of the necessary resources to cope successfully with abnormal requirements contributed materially toward meeting the desired objectives.

Toll Line Equipment. The replacing or No. 3 type of toll switchboard has its toll line signaling units included with the toll line circuit, thus omitting them from the cord circuits in the switchboard and eliminating in many cases the association of ringers with the toll line terminal equipment. This feature required the development of the "applique" devices for use in working old and new sections temporarily together, as already referred to. Fig. 4 shows the arrangement of equipment and cross-connections in a toll line and toll switching trunk.

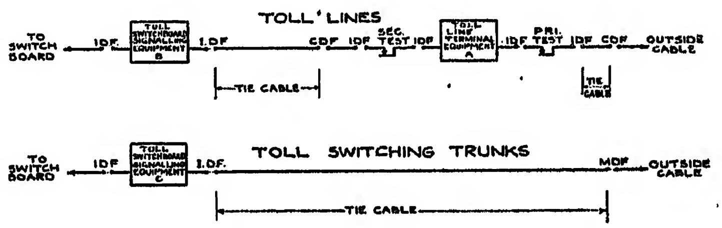

Fig. 4—Diagram Showing Routing of Lines from Outside Cable to Switchboard

CDF = combination distributing frame: *IDF* = intermediate distributing frame: *MDF* = main distributing frame

The toll line signaling unit receives the incoming a-c. and transmits it as d-c. to light the necessary switchboard lamps. It also, under the control of the cord circuit, transmits an a-c. signal of either 20-, 135-, or 1000-cycle frequency to the distant office, depending on the length and type of toll line.

The toll line circuit contains relays for the operation of the signaling unit, a pad control, the line signal, and transfer and multiple cut-off features.

The amount and type of toll line terminal equipment depends, for any particular line, on the type of line, the circuit layout, and whether it is also used for telegraph. All toll lines must necessarily be reduced to physical condition at this point, and many must be here equipped with repeaters of the terminal type.

In line with the switchboard replacement, all of the existing toll lines at Chicago required practically complete retermination and realinement, while on a working basis, to meet both old and new conditions. This covered some 3122 signaling units, 2450 toll line circuits

and 974 two-wire and 1210 four-wire repeaters with their associated networks and equipments. A feature of this work was the necessary coordination by many distant toll line offices and their terminal arrangements.

Repeater Pad Control. For many years necessary amplification of the speech currents on toll circuits switched at the toll office for the longer distances, has been provided by the use of manually operated repeaters of the cord circuit type, available for insertion in the line as required. These were completely displaced at Chicago under the conversion.

The plan carried out to displace the cord circuit repeaters and to obviate certain operating difficulties requires the operation of the toll lines at transmission equivalents low enough to permit switching without cord circuit repeaters. Since, in many toll lines, this would involve noise and cross-talk when they are used on terminal connections, the power level of such a line is reduced by the insertion of a pad when used for a

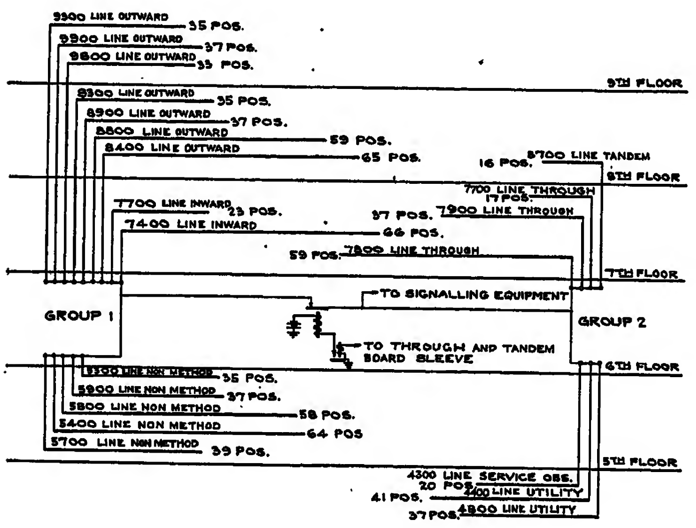

FIG. 5—DIAGRAM SHOWING CONNECTION FOR MULTIPLE CUT-OFF

terminating connection. The plan, therefore, requires circuit arrangements so that the pad will remain in the line when it is used on a terminal connection, but will be removed from the line when it is switched to another toll line on a via connection.

These pads, as has already been stated, are a part of the toll line equipment and their control is obtained by the toll line, trunk, and cord circuit equipments. The pad remains in any toll line when it is connected to an operator or to a toll switching trunk but is removed when it is connected to another toll line and the Chicago operator has cut out her set from the connection.

Multiple Cut-off. The amount of wiring necessary to connect lines in a large switchboard installation where the boards are located on several floors introduces transmission losses due to the bridged multiple and this is objectionable. Arrangements have, therefore, been made to cut off some of the boards for through connections. This is accomplished by so wiring the switchboards that they may be divided into two groups, (1) those at which switches to other toll lines are never made and (2) those at which switches to other toll lines are made. A relay system is then provided so that when a circuit is taken up at any position of group (2), the multiple of the positions in group (1) is cut off. This arrangement is shown diagrammatically in Fig. 5.

Testing. The testing and correcting of troubles on lines and equipment in so large a concentration requires appreciable specialization. A total of 46 primary and 20 secondary units of No. 5 type toll test board are provided for this purpose, with segregation between toll cable and toll open wire terminations. The primary units test against outside and the secondary units against inside office trouble.

In addition to the routine tests made at frequent intervals by the maintenance people routines have been set up for reporting the troubles of various kinds which are noted by the operators. These provide for the prompt reporting of all such troubles to the proper plant maintenance people who take immediate steps to clear up any unsatisfactory conditions.

Power Plant. The toll line terminal equipment requires two 24-volt batteries arranged in parallel, with a 6400-ampere hour capacity and a present peak load of 850 amperes; a 130-volt storage battery unit, with a 640-ampere hour capacity and a peak load of 75 amperes, for the plate voltage of vacuum tubes and for telegraph, and two 1000-cycle and two 135-cycle generators to supply the necessary alternating current for signaling purposes.

The toll switchboard equipment is operated by another 24-volt storage battery unit, with an existing peak load of 1350 amperes; a 28-volt battery used for busy signals, with a 1900-ampere drain in the busy hour; a 130-volt battery for vacuum tube plate current, with a 1.5-ampere drain and a 48-volt battery for special circuits, with a 5-ampere drain. All of these batteries are maintained on a continuous float basis and are provided with voltage regulators. Direct-current power supply operates the charging generators. Alternating ringer current for signaling purposes is here supplied by four 1000-cycle, two 135-cycle and two 20-cycle ringing generators.

The exhauster used for operating the pneumatic tube system is operated by an 85-hp. motor with a speed of approximately 3500 rev. per min.

Toll Line Facilities. The Chicago Toll Office is the center for 20 toll cables entering over six main underground routes, shown in Fig. 6, and terminating 1949 quads of facilities on the cable test boards.

There are, in addition, 152 open-wire circuits which reach the open-wire test board after their preliminary transfer at the city limits to necessary underground toll entrance cables. The routing of the open-wire lines is shown in Fig. 7.

The rapid extension of the toll cable network, by reason of the volume of toll facilities required and their better protection by cable, tends to make any growth in toll open wire seem relatively unimportant. It must be appreciated, however, that there is still an economical necessity for the continuance of an appreciable amount of this type of plant and for additions to it.

In addition to the use of toll open wire for straight circuit provision, it is highly efficient for multiple communication channel purposes. While these may be imposed to some extent on circuits in cable, it is

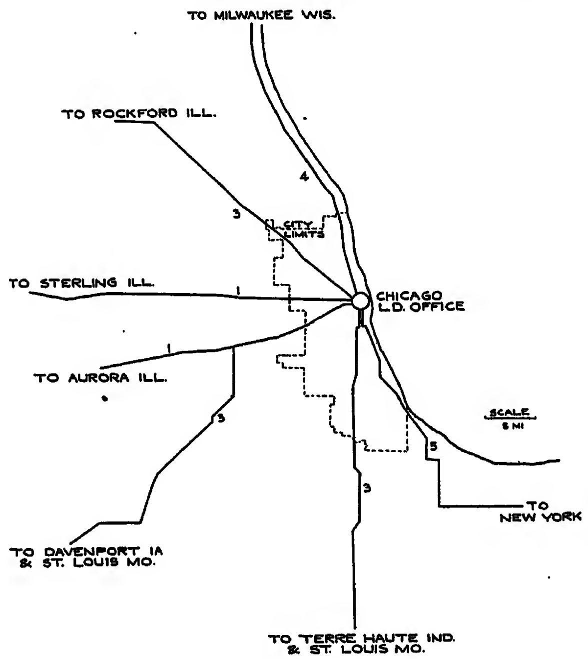

FIG. 6—ROUTE OF TOLL CABLES ENTERING CHICAGO
Figures indicate the number of cables in each route

desirable to locate carrier telephone and high frequency carrier telegraph equipment on the open-wire lines with as little cable as possible, since the cost of loading cable to transmit frequencies up to 30,000 cycles is considerable and the attenuation is large.

At the toll open-wire entrance point, there are now installed, therefore, besides the necessary open-wire terminal equipment and 132 telephone repeaters, 192 channels of carrier telegraph and 37 systems of telephone carrier.

In addition to the 1400 toll lines now in service within toll cables there are 590 telegraph channels in service in these same cables. Of these 300 are superimposed on wires used simultaneously for telephone circuits and the remaining 290 are provided upon carrier-current channels on wires which cannot simultaneously be used for talking purposes.

Toll Traffic. The large capital investments in the general toll plant and the expenses incident to its operation and maintenance are controlled by the volumes of toll traffic which it is anticipated will require handling by it. Since time is a factor in the engineering, manufacture, and placement of the plant, and in the employment and training of the personnel to operate it, these traffic anticipations must be upon the basis of considerable futurities, which vary from several years for switchboards to the annual seasonal peaks for toll lines and detailed monthly estimates for the operating forces.

Various statistical methods are open to use in determining what the future toll traffic will be. In general, these project past averages on future average trend lines, with past occurrences which have caused known distortions removed and proper allowances for future fluctuations included. Mathematical comparisons are checked by judgment which observes not only local but neighboring and country wide controls and potential factors, such as the general business curve.

Estimated originating call volumes must be distributed by terminating points and assembled by route paths and then combined with average conversation lengths and holding times to obtain the call-minute quantities from which toll circuit requirements are finally evolved. These same originating call volumes must be distributed by type of call and combined with operator work time allowances to obtain the traffic unit quantities from which toll switchboards position

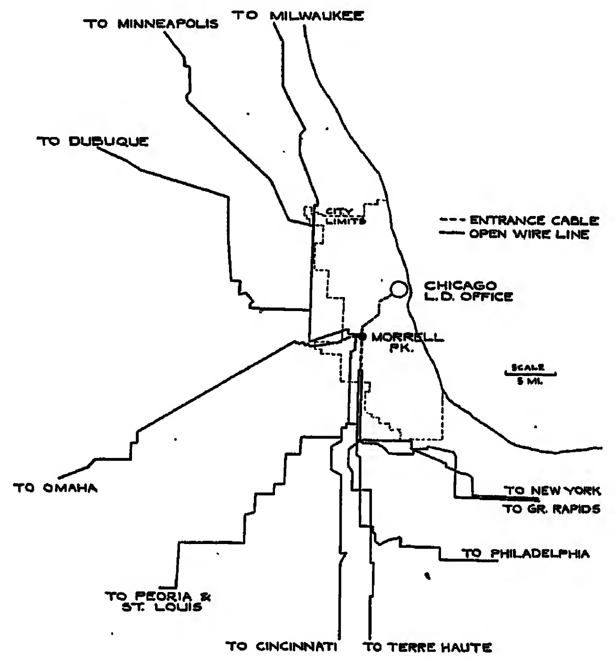

FIG. 7—ROUTE OF OPEN-WIRE LINES ENTERING CHICAGO

requirements can be set up, and the operator force requirements to operate them can be determined.

These functions of traffic toll line, traffic switchboard, and traffic force engineering are necessarily combined with general transmission, toll cable design, switchboard, terminal, and power engineering, and with traffic methods, traffic organization, and traffic operating supervising work to form a completely coordinating and efficient and economical toll system plan.

CONCLUSION

Within this toll system plan the continual objectives are those of simplification and improvement in methods,

increase in speed and accuracy of service, more complete efficiency in the provision and use of plant, and uniformity of transmission between all points.

The marked and steady increases in toll business at Chicago and throughout the country, and the several reductions in toll rates which have been made in recent years are rather direct evidence that these technical objectives are being met to the increased comfort and satisfaction of the subscriber whose point of view is, in the last analysis, the final and ultimate control.

Addendum

(a) *CLR positions,* divided into four units, each serving a selected group of Chicago local offices, record all toll calls originating within these groups and make a first attempt to complete all calls capable of an immediate start. These comprise 85 per cent of the traffic offered.

(b) *Non-method positions,* arranged with selected groupings of toll lines, handle those originating calls which do not result in conversation on the first attempt, such as those upon which "leave word" requests are made, and calls not subject to CLR handling, such as large lists of sequency calls. When a person previously unavailable becomes available and reports that he is ready to talk, the call starts from these positions.

(c) *Utility positions* are specially arranged to concentrate the use of long haul terminal and through circuit groups for outward, inward, and through business at one definite location. For such groups, which include the transcontinental circuits, the utility method is employed in order to obtain more efficient use of the circuits.

(d) *Inward positions* handle all calls incoming from distant offices to stations served by the Chicago local offices and these positions therefore have access to the toll switching trunks to these local offices. The toll lines used for outward service at the line boards appear with lamp signals for incoming service at the inward boards.

(e) *Through positions* are required to establish connections between other toll centers directly connected with Chicago but not with each other. No connections are made to Chicago stations, and the cord circuit repeaters, formerly a significant feature of this board, are now replaced with a terminal type, with automatic pad control.

(f) *Directory positions* are provided to secure the minimum delay in providing the distant station number in cases where the number is not known to the calling subscriber.

(g) *Routing positions* enable certain operators to specialize in quoting the necessary toll circuit information to CLR and "through" operators to points not reached over direct circuits. The list of actual toll centers is in itself very large and to this must be added all of the tributaries reached via these centers.

(h) *Delay quoting positions* are provided to inform the CLR operator of the period a call may be delayed when circuits to distant points may have been put out of service, as from storm or other trouble, or the traffic congestion is unusual.

(i) *Traffic trouble positions* provide a centralized bureau for the reporting of all classes of line and equipment trouble.

(j) *Office "B" positions* are equipped with a subgroup to toll switching trunks to local offices, together with multiple of toll terminal lines and supervisory telephone sets. This provides a means for any CLR operator to obtain, for special reasons, any stations in the Chicago centering district.

(k) *Ticket distributing positions* are required to center the toll ticket traffic passing through the pneumatic tube system and to permit its assortment and assignment with the greater efficiencies at the original sending and final receiving ends.

(l) *Ticket filing positions* are required to receive the completed toll ticket memoranda, compute the elapsed conversation time, and proper charges involved, and so file them that they may be easily found, if required, before their final forwarding to the billing department for collection of the toll revenues involved.

(m) *Service supervisors' positions* handle all service criticisms as received from toll users for any cause.

(n) *Service observing positions* permit checks to be made of the actual conditions encountered on any toll connection, together with the operating technique employed, on a sufficient number of sampled calls to enable the service as a whole to be properly gaged.

(o) *Monitor tap positions* enable the individual operator's work to be observed.

Toll tandem positions, in addition to the above, are required for Chicago office switching by reason of the lack of face equipment capacity to put all outgoing toll lines before all CLR operators.

Discussion

R. L. Hartman: As Mr. Neubauer has pointed out, the engineering of toll office equipment and toll circuits is necessarily based on future requirements and any studies in this connection must definitely anticipate the toll service which the subscriber may require in the future. The present method of engineering in which the annual seasonal peak is considered in general takes care of these requirements over an extended period. Despite this generally effective engineering of toll circuits and estimation of traffic increases, there are certain periods when the amount of traffic is not in phase with the engineering and it becomes a problem to engineer the existing layout to meet more nearly the circuit requirements. Moreover, in Chicago, due to its geographical location and far spread layout, it has been found desirable to make more or less temporary changes in the existing layout to care for the sudden loads and emergency traffic peaks that result from sectional storms, earthquakes, tornadoes, and other major disasters. These large and unexpected volumes of traffic originate in areas feeding into and through Chicago and cannot be handled satisfactorily over the regular circuits. It is also often expedient to rearrange the existing layout to take care

of the normal traffic which is delayed over routes that are impaired or completely destroyed by storm breaks, line failures, etc. Further, temporary rearrangement of existing toll circuits for traffic peaks resulting from football games, automobile races, and other sporting events, as well as for localized peaks in connection with special seasons like the peach or cotton season, are desirable and efficient.

The comprehensive network of telephone circuits throughout the United States has made possible the practise of quoting alternate routes for a large part of the long-haul traffic. This regular toll circuit layout is also sufficiently flexible to permit limited additions to a number of existing groups by cutting other paralleling circuits or by building up additional facilities from circuits already in the layout. Chicago, by its geographical location, is the natural switching point for traffic originating and terminating in the Middle West, Northwest, Southwest, and the Mountain States' territories,—areas that are developing quite rapidly from a long-distance telephone standpoint. It is, of course, the logical switching center for transcontinental traffic as well. Consequently, terminating here are direct circuits from all parts of the United States. In addition, the regular circuit layout out of Chicago is such that several routes are generally possible to most of the large cities in this country and Canada. Under these conditions and with a well defined arrangement whereby the Chicago office is closely tied in with Memphis, Louisville, St. Louis, Kansas City, and Minneapolis, a large part of the work of rearranging the existing circuit layout originates here at Chicago.

The magnitude of this work can be better understood by the quotation of some figures. During recent concurrent storms in the Chicago territory and areas north and south, 120 circuits were rearranged in a 24-hr. period to take care of the normal traffic over the routes affected by the storms. An average of 20 rearrangements per day is made either to make good facilities in trouble, or to adjust for unusual traffic loads. For example, the Chicago-New York group was increased approximately 50 per cent during the recent stock market upheaval at the expense of other circuit groups but not to the detriment of the traffic over the groups used.

It will be appreciated that this "rearrangement" of existing facilities cannot be a haphazard affair but that there must be excellent and up-to-the-minute information available on the circuit groups in the Chicago board and the Western Division as a whole. In general, circuits are taken from groups over which traffic is being moved at the time without delay and it is only under the worst conditions that an attempt is made to equalize delays on various groups that can be used as interchangeable routes. Transmission is carefully considered and the additional switch often introduced by patching must not present an unjustified hazard.

Close co-operation is essential between the various departments involved in engineering a patch and arranging for it in the circuit layout. The new circuits put in the toll board must be properly marked and the operating personnel informed so that the greatest use is made of the circuits established.

Summarizing briefly, the efficient use of equipment and circuits plays quite as important a part in the general economics as proper engineering, installation, and maintenance of the facilities involved. Circuit engineering must be supplemented by a type of supervision of the current flow of traffic to the end that an overall effective use of the existing facilities will be maintained. The temporary changes in circuit layout which are originated here at Chicago are to this end, and offer effective assistance in moving congested or delayed traffic and in maintaining satisfactory relations with the users of long distance service in the Long Lines Western Division comprising approximately 75 per cent of the United States.

W. M. Jamieson: This paper refers to the testing required to operate and maintain the toll circuits in a satisfactory condition. The general inprovement in transmission and the increase in the speed of completing calls, such as is obtained through the use of the "CLR" method of operating, results in stricter requirements on the efficiency obtained from the toll circuits. Some time ago the volume efficiency of the circuits was stressed more than other transmission features. It was recognized that the real measure of transmission is the clearness and distinctness with which the telephone conversation was carried on, *i. e.*, upon the intelligibility of the words and the naturalness of the voice. In a broader sense, transmission depends upon many factors, including volume, distortion, noise, crosstalk, and transient currents. In the design of toll circuits, these factors must be considered in determining the type of facilities required for a certain length of circuit. The efficiency of circuits is now graded in terms of "Effective Transmission Equivalent" which includes allowances for the interfering effects mentioned above. In order to meet the transmission requirements of the various types of facilities involved, transmission tests are made before placing the circuit in service and thereafter at periodical intervals. These tests include transmission frequency runs, noise tests, quality tests, crosstalk tests, balance tests at repeater offices, line insulation and resistance unbalance tests, etc.

To take care of this feature, there are 16 transmission measuring sets installed in the Chicago Office. The tests made include between 11,000 and 12,000 single frequency measurements each month in addition to those mentioned above.

Due to the large number of switchboard and testboard positions involved in handling circuit trouble, a special setup is required to see that all trouble reports are forwarded to the proper party. On discovering a circuit in trouble, the line operator reports the trouble to the traffic trouble clerk, on a special ticket sent over a pneumatic tube. This trouble clerk arranges to make the circuit busy at the tandem board and at the same time reports the trouble to the testboard trouble clerk over a printer circuit. The Traffic Control Bureau receives the report over the same printer circuit. The testboard trouble clerk forwards the report to the proper testboard position over a pneumatic tube. After the trouble on the circuit has been cleared, the testboard man arranges directly with the tandem operator over a telephone order circuit to remove the busy signal, after which he returns the trouble ticket with a notation of the trouble found to the testboard trouble clerk. The report of the trouble being cleared is then sent to the traffic trouble clerk over the printer circuit. By utilizing telegraph printers, pneumatic tubes, and telephone trunk circuits, the circuits are placed back into service with a minimum of lost time and at the same time give an accurate record of the troubles found. In addition the Traffic Control Bureau is able to keep in constant touch with the number of circuits available for service. The feature of the testboard man arranging directly with the tandem operator to clear the busy signal saves from three to four minutes in lost time.

Mention is made of the large concentration of toll telephone and telegraph facilities in toll cables. The protection of this cable plant is a matter of great concern, since the loss of one or more cables would result in a very serious service impairment. Insulation tests on spare pairs in these cables are, in general, made hourly and more frequently in adverse weather. In addition, a portion of the working pairs is successively tested each night so that all conductors in each cable are tested at least monthly. Upon the first sign of a threatened failure, splicing and construction crews and sections of emergency cables are dispatched to the measured location of the trouble. Inspection of the cable in the suspected location is made and if no evidence of a sheath break is found through which moisture could penetrate, a test opening is required. When the sheath break is found, the cable can often be boiled dry with hot paraffin. Sometimes the moisture can be eliminated or reduced sufficiently to permit service by applying oil pumped nitrogen gas to the cable at the manholes adjacent to the sheath break. If the cable is thoroughly satu-

rated, the above methods are usually not successful and an emergency section of cable must be pulled in place and spliced to replace the faulty section. Emergency supplies of gas and cable are stored at strategic locations in both the metropolitan and suburban areas. Cable crews engaged in repair or construction work are required to call a central point periodically so the nearest crew can be utilized in an emergency and the cable restored in the shortest possible time.

Many cables are placed under permanent pressure using nitrogen gas with an alarm system so as to increase the speed of clearing sheath breaks. Experience so far indicates that only 1/8 as many service interruptions occur on aerial cable under pressure, and 1/75 on underground cables as compared to those not under pressure. At present there are six toll cables out of Chicago under gas pressure and plans have been made to place the toll cables under pressure by the end of 1929.

H. S. Osborne: The very great development of toll business has greatly increased the importance of improving the means for interconnecting the small toll centers of the country for taking care of the extremely large number of relatively small items of traffic between widely distant points.

There are about 2700 toll centers in the United States through which this traffic is handled, and the problem is to provide a routing so that any one of those 2700 toll centers can be connected to any other one rapidly, with a minimum number of switches and with adequate clearness of transmission.

Fortunately, the development of the business and of the changes in practise has helped in bringing about improvements in this general problem of switching.

There has been a very marked tendency toward an increase in the concentration of toll circuits along a given route. With the old practise, where we were relying on open wire lines, a toll line carrying 40 wires and 30 circuits constituted a heavy route. Now a single aerial cable toll line carrying two cables will have as many as 600 circuits. On the most important routes of the country are being developed underground cable routes which will ultimately carry many thousand toll circuits. This tendency for concentration on toll routes has its parallel in the practicability of setting up simplified and improved toll switching systems.

There have been selected out of the 2700 toll centers in the country 150 important switching centers which are designated as primary outlets, and, as indicated by that name, those points are the points through which the switched business of the toll centers is primarily handled, although not exclusively, because alternate routes are provided where they are economically warranted.

These primary outlets are interconnected by direct circuits within as large areas as practicable, generally within a State, which means that within such an area any two toll centers can be connected together with a maximum of two intermediate switching points. That constitutes a material improvement in the handling of these items of switched business over the arrangements which were practicable before. It reduces not only the number of switches but helps greatly in making it possible to provide adequate transmission.

To handle the countrywide business, there have been selected, as was shown in the chart in Mr. Neubauer's paper, eight regional centers, and each primary outlet is connected to at least one of these regional centers. Chicago is probably the most important of those regional centers, there being already direct circuits to Chicago from 75 out of the 150 primary outlets of the country, so we might say, roughly, that half the telephones of the country can talk to Chicago without more than one intermediate switch. If they do not want to talk to Chicago, they still find Chicago a very important point in the process of getting through connections to other distant parts of the country.

J. A. Caparo: What relation exists between the different signaling frequencies and the efficiency of transmission?

E. O. Neubauer: On telephone lines the frequency of 1000 cycles is the most efficient of the three. The frequency bands of the telephone lines are such that the lower frequencies are transmitted with rather low efficiency, as I said before in connection with the 20-cycle system. For that very reason 20 cycles is suitable only for short circuits and those not equipped with telegraph apparatus. The 135-cycle systems are used more extensively but on account of the low efficiency of telephone lines at that frequency, frequent repeaters of that 135-cycle current are necessary. But the 1000-cycle system being a very important frequency in the voice range, is transmitted with considerable ease over the telephone line. In other words, the transmission frequency characteristics of the toll line are rather poor at frequencies as low as 20 cycles, and they become comparatively very efficient at frequencies over 200 up to about 3000 cycles.

Air Transport Communication

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and

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Synopsis.—The successful operation of an air transportation system depends in no small degree on the communication facilities at its command. Rapid and dependable communication between transport planes in flight and the ground is essential. Two-way radio telephony provides this necessary plane-to-ground contact.

The design of a radio telephone system for this service requires quantitative knowledge of the transmission conditions encountered in plane-to-ground communication. An experimental investigation of these conditions over the available frequency range has been carried out and the results are described.

A complete aircraft radio telephone system designed for the use of air transport lines and an airplane radio receiver designed for reception of government radio aids to air navigation are also described.

INTRODUCTION

PROBABLY nothing has contributed more to the safety and reliability of present long distance transportation systems than the associated communication and signaling facilities. With ocean-going steamships constant communication is maintained through the medium of the radio telegraph, providing not only the communication necessary in times of emergency or peril, but also routine daily weather information and such instructions as are necessary to insure the safe and efficient handling of ships at sea and in port. Similarly, on our principal railroads, the fastest trains are dispatched by wire telephony and further protected by electrically operated block signal systems.

For airplanes the very great speed and the greater dependence on weather conditions make it necessary to provide more frequent and more complete communication contacts than are required in the case of either ocean or rail transportation. The highest degree of reliability and safety can only be achieved with this mode of transportation when instantaneous communication with ground is available to the pilot throughout his flight. This can only be provided through the medium of radio and preferably by the use of radio telephony, since telephony has an advantage over telegraphy in requiring no skilled operator as well as insuring much more rapid communication. It also has the advantage of making possible direct communication between the pilot and the air transport dispatcher located on the ground, thereby avoiding delay and the possibility of misunderstandings that might grow out of the necessity of transmitting information through a third and perhaps fourth party.

On air lines equipped with radio the dispatcher on the ground provides the pilot in flight with frequent weather reports, information relative to landing conditions, the positions of other planes flying along the same section of airway, and other data which may be useful in safely maintaining a regular schedule. The pilot, in return, keeps the dispatcher informed as to his progress along the airway and the weather conditions encountered. This frequent routine personal contact between pilot and dispatcher insures satisfactory communication in time of emergency. In case of a forced landing the ground organization is advised of the position of the plane and adequate arrangements can be made for the prompt care of passengers, mail, or express.

It is, however, in the avoidance of accident that the radio is vitally necessary. For example, many of our Western airports are reached only by crossing one or more mountain ranges. Frequently upon crossing the mountains a pilot is confronted with a blanket of clouds which must be pierced to reach port. With accurate radio information as to the "ceiling" or height of the underside of the cloud bank from ground, a descent can be made with confidence and safety or, in case of inadequate ceiling, the plane may be diverted to another port.

The problem of designing a radio telephone system to provide service of this character is discussed in this paper which also describes the equipment that has been developed.

TRANSMISSION TESTS

An essential preliminary to the actual design of such a radio telephone system is a decision as to what frequency range the apparatus should be designed to cover. The carrier frequency for any radio service is determined to a considerable degree by the distance over which it is necessary to communicate. As the principal airports along the airways of the United States are, in general, spaced about 200 miles (see Fig. 1), a range of reliable transmission of about 100 miles will insure constant contact between planes in flight and radio ground stations installed at these ports. Experience has shown that the frequency band now employed for broadcast service, that is, 550 to 1500 kilocycles, is well suited for transmission at this distance. However, these frequencies are not available for aircraft communication and consideration was therefore given to bands both above and below this range.

The International Radio Telegraph Convention of 1927 allocated a frequency band of from 315 to 350 kilocycles exclusively to air mobile service. This

1. Bell Telephone Laboratories, New York, N. Y.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

29-151

convention also allocated a number of other bands in the range 350 to 550 kilocycles to general mobile service. These bands have admirable transmission characteristics. However, they provide for but a small number of telephone channels and have the further disadvantage of requiring a very large transmitting antenna which is of course a severe handicap in the case of an airplane

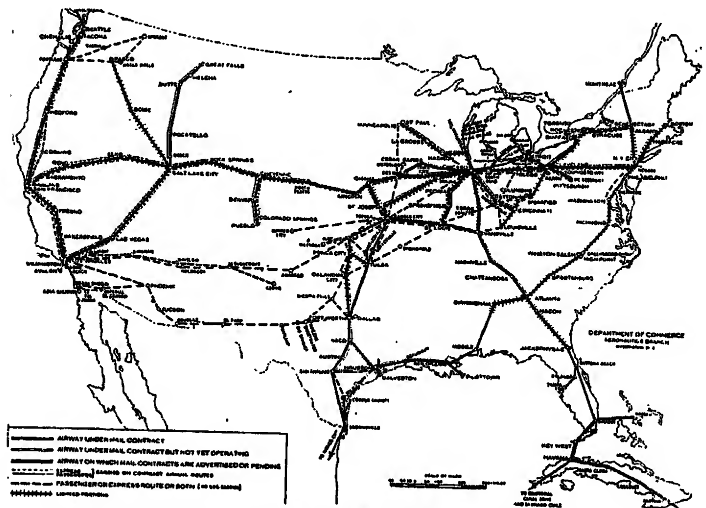

FIG. 1—AIRWAY MAP OF THE UNITED STATES

installation. A number of bands in the frequency range of 1500 to 6000 kilocycles was also allocated to mobile services by the convention of 1927. Attention was turned to this frequency range and experimental

FIG. 2—CABIN MONOPLANE EMPLOYED IN THE DEVELOPMENT OF RADIO SYSTEMS FOR AIRPLANES

tests undertaken to determine its suitability for this class of service.

For the conduct of these tests a five-place cabin monoplane has been operated from Hadley Airport, New Jersey, as a base. Measurements of strength of received signals have been made both transmitting from plane to ground and from ground to plane. In the latter case a radio field strength measuring set was installed in the airplane. These transmission tests have been supplemented by similar tests made in California employing a biplane mail ship.

One of the striking results of this investigation has been the disclosure of the manner in which signals of these frequencies vary in strength with the plane's altitude. Fig. 4 is a record of the strength of signals

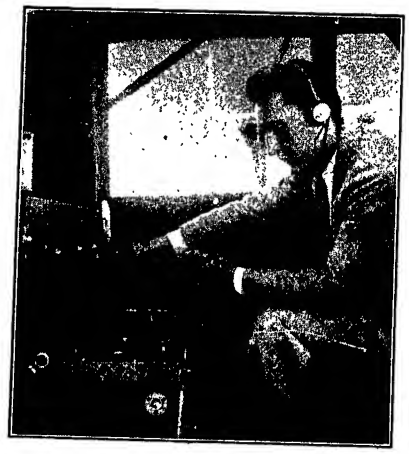

FIG. 3—RADIO FIELD STRENGTH MEASURING SET IN USE IN AIRPLANE

received from a 500-watt transmitter located at Whippany, New Jersey, and operating at a frequency of 1510 kilocycles during daytime flights from Whippany in

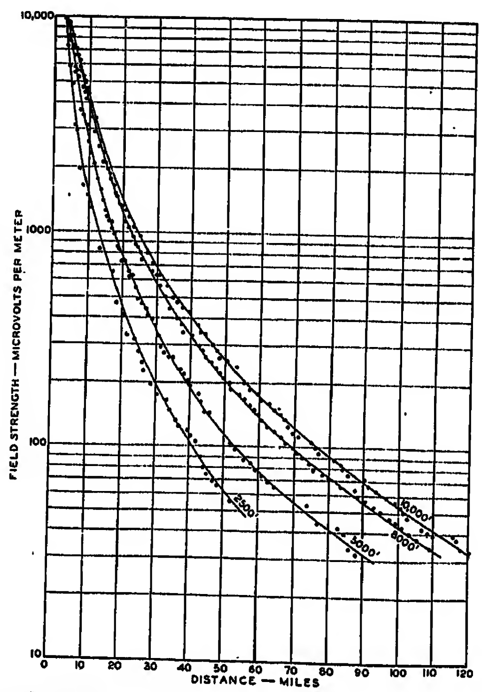

FIG. 4—STRENGTH OF DAYTIME SIGNALS RECEIVED IN AIRPLANE FROM 500-WATT GROUND STATION OPERATING AT 1510 KILOCYCLES

the general direction of Philadelphia. A comparison of the field strength as given graphically by the curves shows the influence of altitude of flight on the strength of signals. Figs. 5, 6, 7, and 8 show transmission from plane to ground to have similar characteristics. These curves are the result of plane-to-ground daytime transmission tests made in California. The curve for each

altitude is the result of averaging the data obtained in flights in three directions from Oakland Airport.

For all of the tests in both California and New Jersey the airplane was equipped with a radio telephone transmitter having a carrier power of 50 watts and a quarter

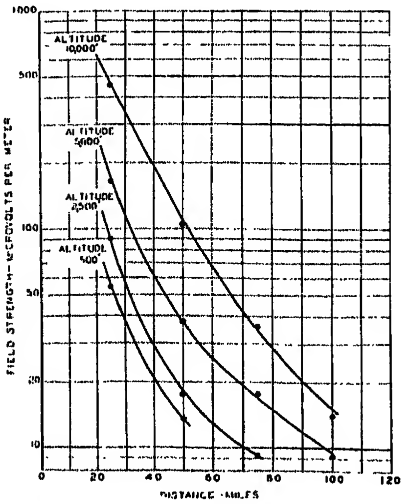

FIG. 5—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 1625 KILOCYCLES

wave trailing wire antenna. During many of these tests the field strength measurements were supplemented by telephone intelligibility tests. These were made by reading lists of 25 disconnected words and endeavoring to record them at the receiving end of the

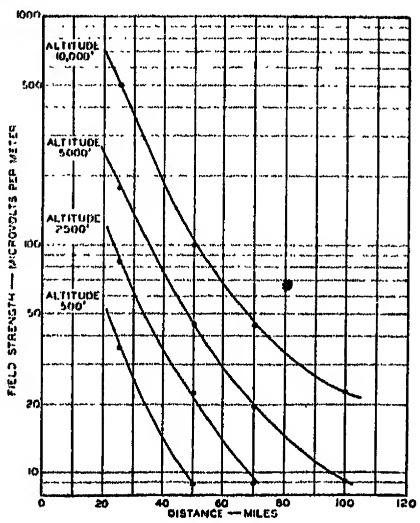

FIG. 6—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 2525 KILOCYCLES

circuit. Fig. 9 shows the results of such tests which were made at the same time that the transmission data shown in Figs. 5, 6, 7, and 8 were taken. An idea of the satisfactoriness of the telephone circuit provided with varying distance and with different carrier frequencies may be had from the curves of Fig. 9. In interpreting these curves, it is to be noted that for the circumstances of these tests a result of 50 per cent or

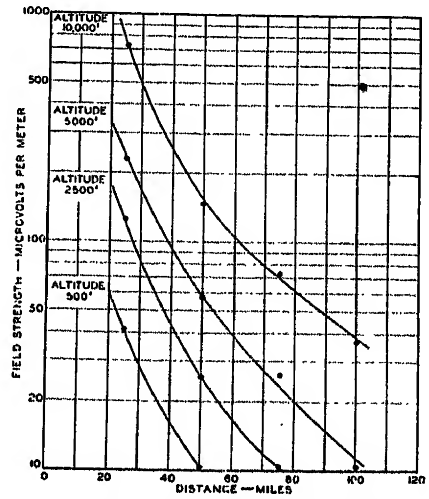

FIG. 7—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 3450 KILOCYCLES

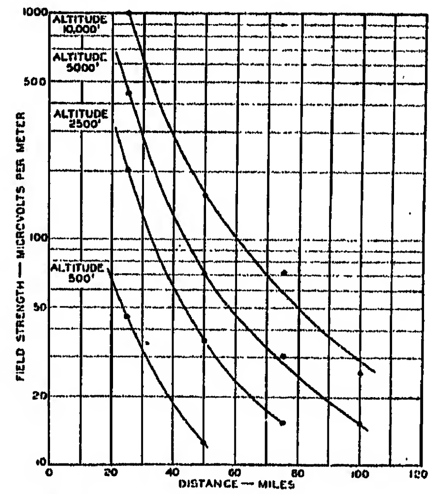

FIG. 8—AVERAGE STRENGTH OF SIGNALS RECEIVED FROM AN AIRPLANE EMPLOYING A 50-WATT RADIO TRANSMITTER—DAYLIGHT TRANSMISSION—FREQUENCY 5630 KILOCYCLES

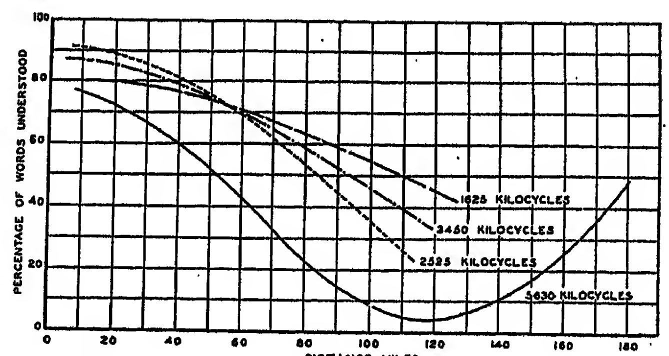

FIG. 9—AVERAGE INTELLIGIBILITY DATA FOR DAYLIGHT FLIGHTS —TRANSMISSION PLANE TO GROUND

better corresponds to a satisfactory condition for conversation.

It will be noted that, in general, greater field strengths

were obtained from the lower frequencies and a higher degree of intelligibility provided. The lower intelligibility at the high frequencies is not alone due to low field strength but also to the fading which occurs at these frequencies. The lower curve of Fig. 9, which is for 5630 kilocycles, indicates the presence of the "skip

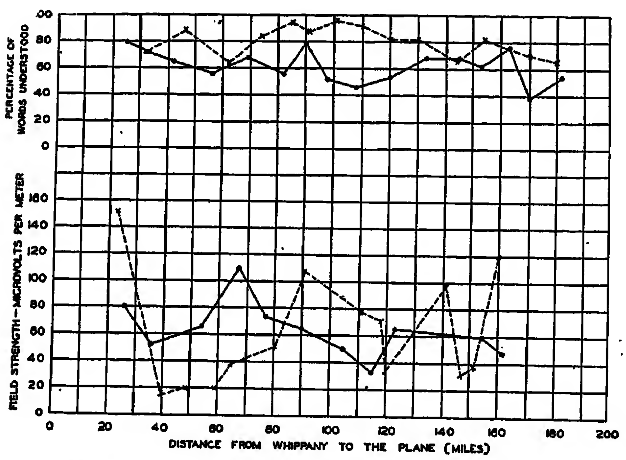

Fig. 10—Signal Strength and Intelligibility Data—Night Transmission—Plane to Ground—Frequency 1608 Kilocycles

distance" effect. This is encountered in the higher frequency range of the band investigated and indicates that while these frequencies will provide satisfactory transmission over quite great distances, they are not so reliable for moderate distance transmission.

Investigations of a similar character in which both

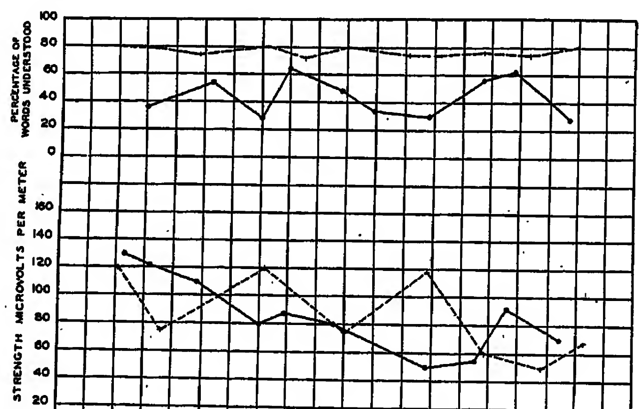

Fig. 11—Signal Strength and Intelligibility Data—Night Transmission—Plane to Ground—Frequency 3452 Kilocycles

field strength and intelligibility tests were made were undertaken in a series of night flights conducted between Hadley Airport, New Jersey, and Washington, D. C., during the month of May, 1929. In this case the transmission was also from plane to ground, field strength measurements being made at Whippany, New Jersey. Figs. 10, 11, 12, and 13 record the results of these tests. Although a great deal more fading was encountered during these tests than during similar ones made in the daytime, as indicated by the percentage of words understood correctly, it was found possible with the three lower frequencies used, 1608, 3452, and 4108 kilocycles, to maintain practically continuous communication with the plane in flight. At each frequency, data were taken for flights both to and from Washington. The dash line curves indicate the data obtained on the trip to Washington and the full lines the return trip. The differences in the data for the two directions

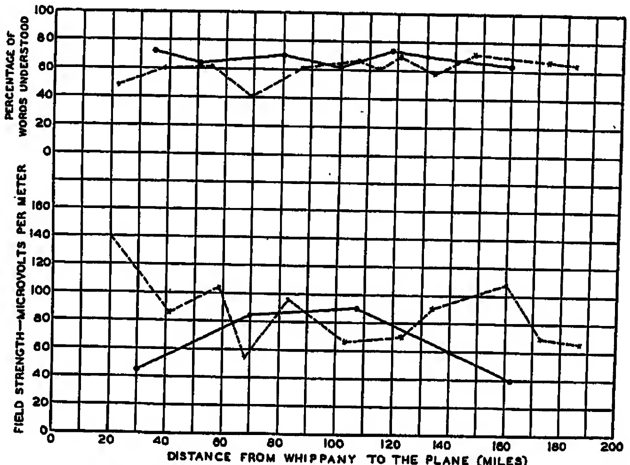

Fig. 12—Signal Strength and Intelligibility Data—Night Transmission—Plane to Ground—Frequency 4108 Kilocycles

are believed to have been due more to variations in the interference present from other stations than to any change in transmission conditions. Examination of the upper curves of Fig. 13 indicates that a frequency of 5690 kilocycles was not satisfactory under these conditions. This was mainly due to excessive fading and accompanying distortion effects.

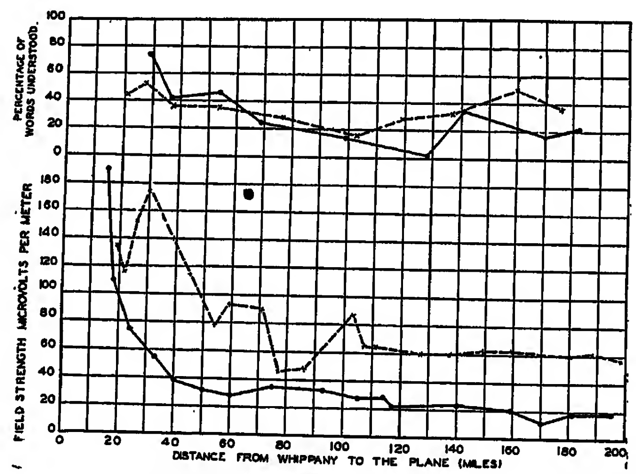

Fig. 13—Signal Strength and Intelligibility Data—Night Transmission—Plane to Ground—Frequency 5690 Kilocycles.

A study of the transmission data presented here and similar data from other tests has led to the conclusion

that in the frequency band 1500 to 6000 kilocycles, satisfactory channels can be found to meet the requirements of domestic air transport operation. In general, the lower frequencies of this band appear to provide the most satisfactory transmission. However, the use of these frequencies is only practical when trailing wire antennas are employed. It may, therefore, be desirable in some cases to use the higher frequencies of

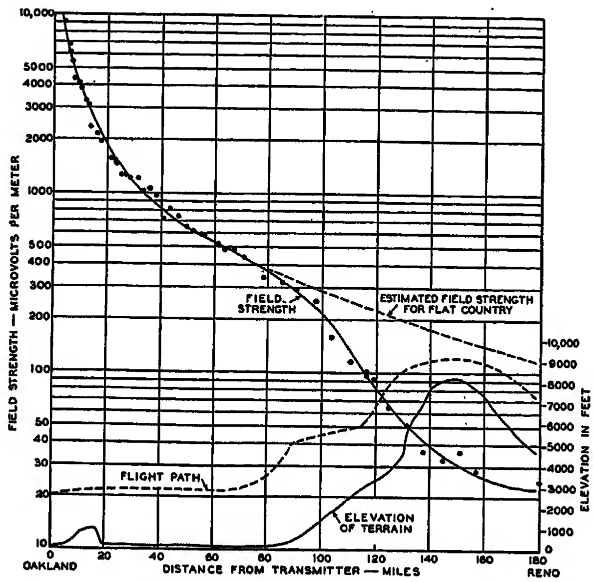

FIG. 14—SIGNAL STRENGTH IN AIRPLANE—RECEIVING FROM 500-WATT 325-KILOCYCLE GROUND TRANSMITTER

the band with fixed antennas of relatively small dimensions in order to avoid the use of the trailing wire which, while being satisfactory from an electrical point of view, offers some mechanical disadvantages. This would somewhat restrict the range of communication but would offer a satisfactory solution of the problem provided ground stations were located at sufficiently frequent intervals along the airways and adequate communication provided between stations.

With an increase of the density of air traffic along the principal airways it is expected that wire telephone facilities will be provided for inter-field communication and for extending the plane-to-ground telephone circuit to distant points on the airway. There is a number of engineering problems involved in the connection of radio and wire facilities so as to provide a comprehensive telephone dispatch system but there appear to be no insurmountable difficulties and such an arrangement has been set up experimentally on frequent occasions at Whippany, New Jersey, where the experimental ground station is located. But traffic on most airways has not yet grown to the point where such a wire telephone network can be justified. A very useful auxiliary service which is also believed to have a permanent place is the telephone typewriter or printing telegraph system which is being used for the interchange of weather information between fields on many of the principal airways.

The band of frequencies of 1500 to 6000 kilocycles is not suited to direction-finding purposes over any great distance. In general, it is necessary to use moderately low frequencies for this purpose and the Department of Commerce, with this in mind, adopted for airway radio beacons the band of frequencies internationally allocated exclusively to radio beacon service (285 to 315 kilocycles). Weather information is usually broadcast in the adjacent exclusive aircraft band, 315 to 350 kilocycles, although at some airports the weather and beacon signals have been alternately transmitted on the same frequency in order to avoid the necessity of the pilot retuning his radio receiver.

To provide information as to the signal strength that would be available at the frequencies of such weather and beacon stations, a number of transmission tests has been made with frequencies in these bands. In this frequency range, little variation in signal strength is encountered with changes in altitude. Fig. 14 shows the results of such measurements made on a flight from Oakland, California, to Reno, Nevada. The signals were provided by a 500-watt radio transmitter installed at Oakland Airport. This curve is especially interesting as it shows the greater attenuation introduced by the presence of a mountain range. The dash curve in this figure indicates the transmission conditions found over flat country.

ANTENNAS

Although the use of trailing wire antennas for aircraft radio purposes has been quite general in military practise for some time, no accurate data have been available as to their resistance characteristics over the frequency range, 1500 to 6000 kilocycles. As this information is necessary in order to properly design

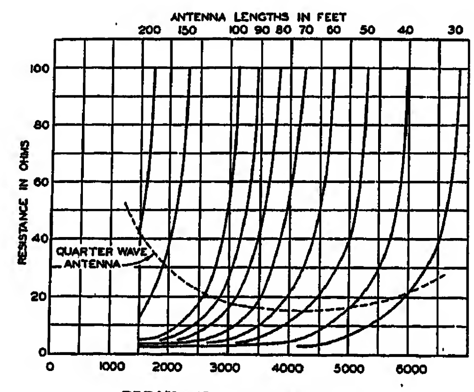

FIG. 15—RESISTANCE CHARACTERISTICS OF TRAILING WIRE ANTENNAS

transmitting equipment for use with such antennas, measurements have been made employing a substitution method. The results of these measurements are shown in Fig. 15. It will be noted that for quarter wave antennas the resistance varies between 15 and 42 ohms.

As to receiving antennas, Fig. 16 is illustrative of a general type of self-supporting, stream-lined mast

antennas which are being widely used with airplane radio receivers for the reception of weather and beacon signals. The mast shown is of hollow wood construction with an internal conductor and extends approximately seven feet above the fuselage of the plane. Similar masts of metal construction may also be sucessfully used.

For transmission they are not generally suitable

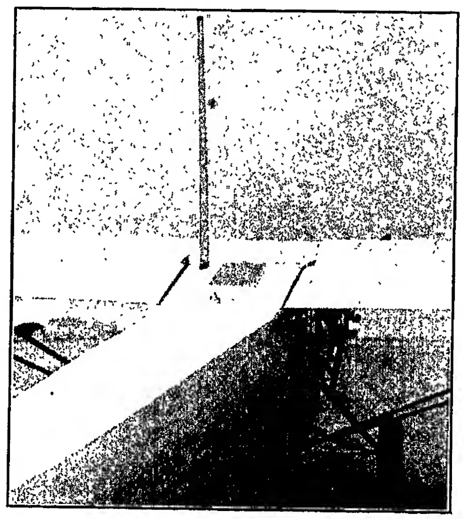

FIG. 16—TYPICAL INSTALLATION OF SELF-SUPPORTING STREAM-LINED VERTICAL ANTENNA FOR RECEPTION PURPOSES

owing to the relatively small effective height of such antenna structures. However, they may be employed at frequencies above 3000 kilocycles but with considerable sacrifice in efficiency compared with that to be had with the trailing wire. In some cases, the efficiency has been increased by the use of an umbrella arrangement formed by guy wires attached to the top of the mast. These guy wires have the disadvantage of greatly increasing the head resistance of the antenna structure, thereby slowing up the plane and reducing its carrying capacity.

GENERAL REQUIREMENTS

Radio apparatus for aircraft installations is called upon to meet more stringent requirements than such apparatus for any other type of service. The principal requirements are reliability and simplicity of operation. In practically all mail planes and many transport planes it is necessary to install the most important apparatus elements in locations totally inaccessible in flight. The equipment is usually operated by one not especially skilled in the manipulation of radio apparatus. In mail planes it must be completely controlled by the pilot. The apparatus must be sturdy and capable of withstanding continual vibration, yet it must be compact and light in weight.

It must meet unusual electrical requirements. For example, with the small receiving antenna usually provided the radio receiving equipment must be unusually sensitive in order to receive satisfactorily the comparatively low field strengths available. It must be capable of delivering a very high output level in order to make the signals audible over the noise of engine, propeller, and wind which is experienced in most present-day planes.

This high acoustic noise level is also an important factor in determining the design of microphones and telephone receivers for use in aircraft installations; and it is necessary in the case of both microphone and receiver to take special precautions to exclude external noise.

The use of radio equipment places some special requirements on the airplane. The usual ignition system is the source of such violent electrical disturbances as to practically preclude the reception of radio signals even over very moderate distances. Interference from this source may be practically overcome by the proper electrical shielding of the ignition system. For entirely satisfactory results, shielding must include the magneto, the low tension magneto circuits, high-tension leads, and the spark plugs. The electrical aspect of the shielding problem is quite simple but the mechanical difficulties encountered are numerous. Recent co-operative attacks on the problem by government departments and radio, accessory, and engine manufacturers have resulted in considerable progress and shielded ignition systems having electrical and mechanical characteristics, equal if not superior to the unshielded systems, are being made commercially available. Should engines of the Diesel type come into general use, the shielding of ignition systems will cease to be an important problem.

In addition to shielding, it is desirable to bond all metal parts of the plane in order to avoid noises in the

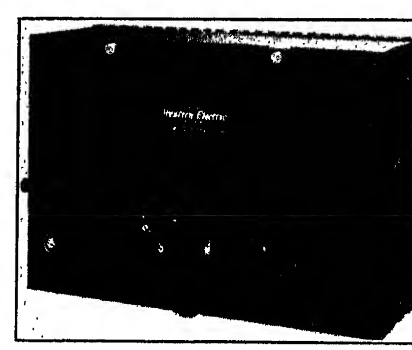

FIG. 17—AIRCRAFT RADIO RECEIVER FOR WEATHER AND BEACON RECEPTION

receiving equipment from intermittent contacts between various metal parts of the plane. In case transmitting equipment is installed, such bonding is essential protection against the possibility of high voltages developing between such parts and resultant sparks or arcs. In planes of all-metal construction the provision of such bonding is a comparatively simple matter.

AIRPLANE RADIO RECEIVERS

Fig. 17 shows a radio receiver designed for reception

of the government weather and beacon signals over the frequency range 285 to 350 kilocycles. The design of this equipment was given precedence in our program over the design of a complete two-way radio telephone system in order to make the government radio aids to air navigation available as soon as possible. This equipment, however, constitutes a desirable supplement to the two-way system. This 8-A receiver is of high sensitivity, an antenna input of 10 microvolts

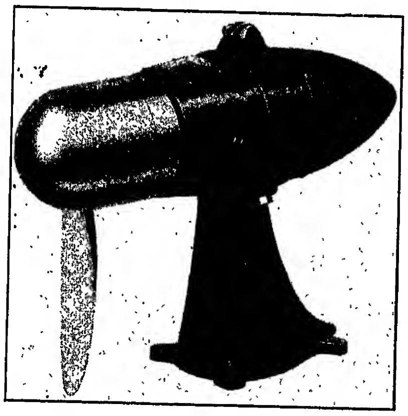

FIG. 18—WIND-DRIVEN GENERATOR FOR SUPPLYING FILAMENT AND PLATE POWER FOR AIRCRAFT RADIO RECEIVERS

being sufficient to enable it to deliver an audio frequency output of 6 milliwatts. It can be expected to give consistent reception for government weather reports from the 2-kw. ground stations at a distance of 125 miles; and it has been successfully used at a distance of 200 miles.

Equipotential cathode vacuum tubes are employed throughout the receiver. The cathode of each tube is heated indirectly from an auxiliary filament. This arrangement eliminates the possibility of the introduction of noise from the filament supply source. Four tubes are used in the receiver. Three are of the shield grid type, two being employed as radio frequency amplifiers and the third as a detector. The fourth does

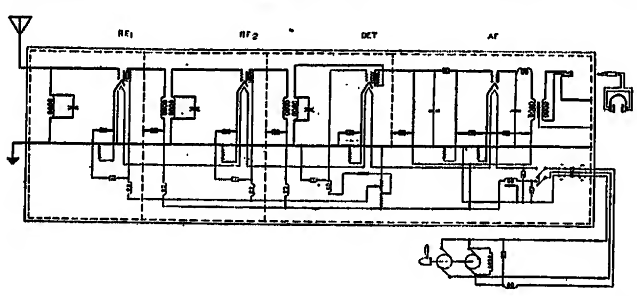

FIG. 19—SCHEMATIC CIRCUIT OF LOW-FREQUENCY AIRCRAFT RADIO RECEIVER FOR WEATHER AND BEACON RECEPTION

not contain a shield grid and is employed as an audio frequency amplifier.

The circuit arrangements are shown in Fig. 19. There are three tuned circuits, one for the antenna and one for the output circuit of each of the stages of radio frequency amplification. A special gang condenser is employed for simultaneously tuning these three circuits. The amplification of the receiver is controlled by a potentiometer which varies the shield potential of the two radio frequency amplifier tubes.

The receiver is mounted in a metal box about 12 in. long by 8 in. high and a little over 4 in. deep. Complete with vacuum tubes, it weighs about 13 lb. Both filament and plate supplies may be obtained from a small wind-driven generator having a diameter of only

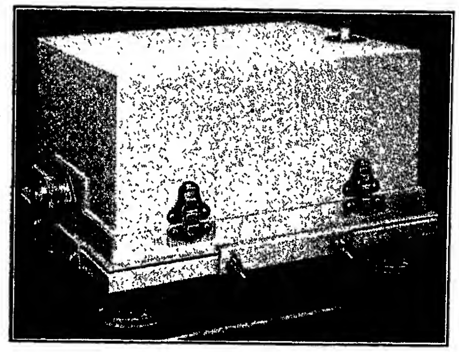

FIG. 20—HIGH-FREQUENCY REMOTE CONTROLLED AIRCRAFT RADIO RECEIVER FOR TWO-WAY COMMUNICATION

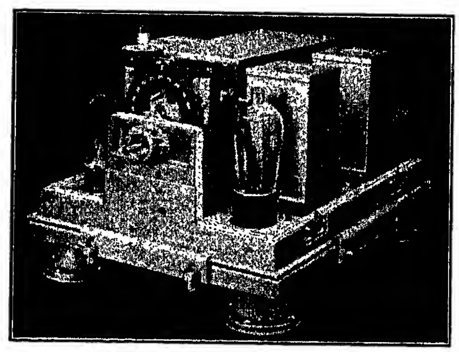

FIG. 21—HIGH-FREQUENCY REMOTE CONTROLLED AIRCRAFT RADIO RECEIVER FOR TWO-WAY COMMUNICATION—COVER REMOVED

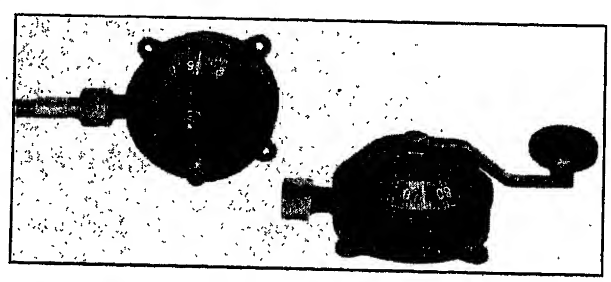

FIG. 22—REMOTE TUNING CONTROL FOR AIRCRAFT RADIO RECEIVERS

a little over 3 in. Complete with propeller, it weighs only about 7 lb. This generator is driven at 6500 rev. per min. by a constant speed propeller. A dynamotor has also been successfully used for furnishing the plate supply for this receiver from a 12-volt battery in ships so equipped. The battery is then used directly for the excitation of the filament circuit.

Figs. 20, 21, and 22 show a design of aircraft radio

receiver designed for remote control. Two receivers of this general design have been developed, one with a frequency range of 250 to 500 kilocycles for beacon and weather broadcast reception and one with a range of 1500 to 6000 kilocycles for two-way communication.

The circuit arrangement in each of these receivers is similar to that of the 8-A already described for weather reports and broadcast as will be seen by a comparison of Figs. 23 and 19. An additional radio frequency input stage has, however, been provided. This input stage, while not tuned to the carrier frequency to be received, is provided with a special input filter, to avoid interference from unwanted stations which sometimes results from detection or modulation in such untuned amplifiers. Arrangement is also provided for adapting the receiver to antennas of various dimensions.

Remote volume control is accomplished by mounting the potentiometer which controls the shield grid potential of the radio frequency amplifiers in a small unit which is located within reach of the pilot. The

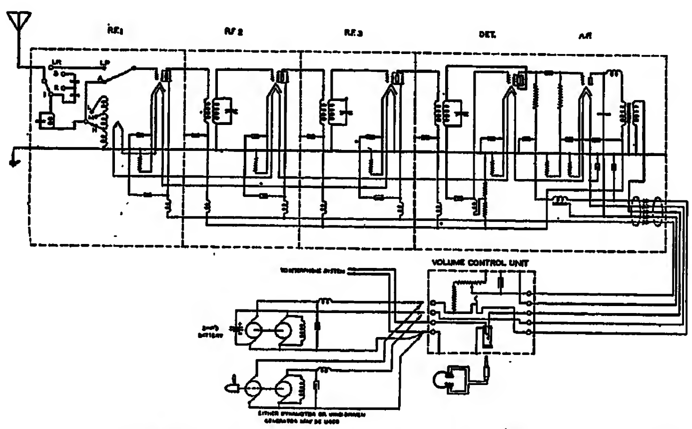

FIG. 23—SCHEMATIC CIRCUIT OF HIGH-FREQUENCY AIRCRAFT RADIO RECEIVER

remote tuning is accomplished by the use of a flexible shaft operated at a speed 264 times that of the condenser shaft. The radio receiver may be located as much as 35 to 40 ft. from the pilot and the tuning accomplished with practically no backlash. The receiver, while necessarily of light and compact construction, is extremely rugged, a cast aluminum bedplate forming the base for the support of all the apparatus units. Thorough shielding is provided for the circuit elements and the tuning coils are mounted in individual copper shielded containers. These coil assemblies plug into sockets similar to those provided for the vacuum tubes. Three sets of coils are employed to cover the frequency range of 1500 to 6000 kilocycles. A welded sheet aluminum top cover protects the apparatus from dirt and moisture.

A cushioned mounting base is provided for these receivers. This base is permanently installed in the airplane and the receiver may be readily removed therefrom. A single plug connector provides for all power supply and output leads from the radio receiver. This is quickly detachable from the receiver as is also the flexible cable which attaches to the condenser driving head. The receivers are about 6 in. by 10 in. by 12 in. and weigh about 16½ lb. complete with tubes.

AIRPLANE RADIO TRANSMITTER

Figs. 24 and 25 show the radio transmitter which

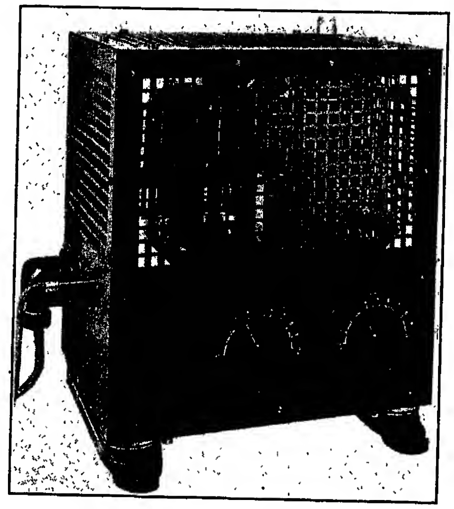

FIG. 24—HIGH-FREQUENCY AIRCRAFT RADIO TRANSMITTER FOR TWO-WAY COMMUNICATION

has been designed for airplane installations. This transmitter has a carrier output power of 50 watts and is capable of complete modulation. A transmitter of this power was designed as the transmission tests

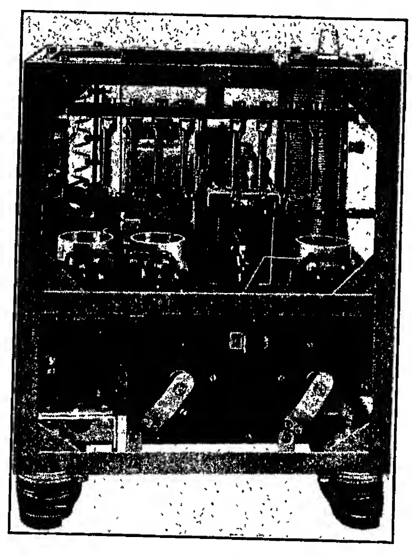

FIG. 25—HIGH-FREQUENCY AIRCRAFT RADIO TRANSMITTER FOR TWO-WAY COMMUNICATION—FRONT PANEL REMOVED

described had shown it to provide a satisfactory range and it could be built of reasonable size and weight. Moreover, its power supply requirements are moderate and can be met satisfactorily in the present size planes.

The transmitter may be adjusted to any frequency in the range of from 1500 to 6000 kilocycles. The

effective use of the frequency range available for aircraft two-way communication requires that the stations be maintained closely upon their assigned frequency. This has been accomplished in the design of this aircraft radio transmitter by the employment of a quartz crystal controlled oscillator. The quartz crystal is clamped firmly between two metal electrodes, the lower one of which is held at a temperature of 55 deg. cent. by an imbedded electrical heater controlled by a thermostat of the mercury-column, contact making type. The entire unit is enclosed in an isolantite housing and arranged to plug into a socket similar to those employed for the vacuum tubes.

The crystal controls the frequency of the oscillations generated by a 5-watt vacuum tube. It is so ground that these oscillations have a frequency of one-half that which it is desired to radiate. A second 5-watt vacuum tube is employed as a frequency doubler. The output of this doubler tube excites the grid circuit of a final radio frequency amplifier which delivers a carrier power of 50 watts to the antenna circuit. This final stage of amplification is neutralized. The plate supply to this

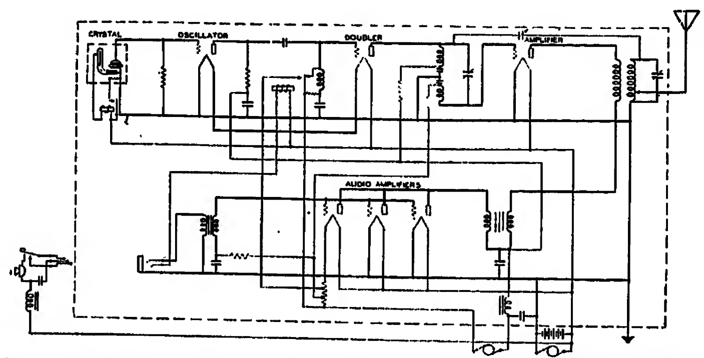

FIG. 26—SCHEMATIC CIRCUIT OF HIGH-FREQUENCY AIRCRAFT RADIO TRANSMITTER

final amplifier is modulated by the introduction into its plate circuit of the speech frequency output of three 50-watt tubes connected in parallel. The grid circuit of this audio amplifier is fed from the output of the airplane microphone through an input transformer. The transfer of the audio frequency power from this amplifier to the plate circuit of the radio frequency amplifier is through a transformer designed to properly adjust the impedance of the load circuit. D-c. saturation is avoided in this transformer by so arranging the windings that the magnetization due to the plate current of the radio frequency amplifier tends to balance that produced by the plate current of the audio amplifier.

The transmitter, like the receivers, is arranged so that it may be quickly removed from an airplane. All power supply to the transmitter is fed through a readily removable plug provided with a locking ring. The speech input and the control circuits for starting and stopping the oscillator are connected to the transmitter through a three-conductor telephone plug. The transmitter measures about 9 in. by 12 in. by 15 in. and weighs, complete with crystal holder and vacuum tubes, 32 lb.

TWO-WAY SYSTEM

The plane terminal of the two-way telephone link is comprised principally of the radio receivers and transmitter described. It is to be noted that "push-button" operation is used. This appears to be desirable on account of the close juxtaposition of the apparatus on the plane and for conservation of frequencies. The short-wave system is so designed that the same carrier frequency may be used both for plane-to-ground and for ground-to-plane transmission. In addition to the things which have been described there is a number of important accessories which are of interest in understanding the operation of the system.

The radio transmitter requires for its operation a d-c. plate supply of 400 milliamperes at 1050 volts and a filament supply of about 15 amperes at 10 to 12 volts. A typical power supply system consists of a 12-15-volt, 50-ampere automatically regulated generator gear connected to the airplane engine, across which is connected a 6-cell, non-spillable lead storage battery of 65 ampere-hours capacity. The filaments of the transmitter are fed directly from this generator-battery combination and the plate supply obtained from a dynamotor operating from this same supply. A smaller dynamotor supplies the 215-volt plate supply necessary for the receiver plate circuits. Double voltage engine-driven and wind-driven generators furnishing 12-15 volts for battery charging and 1050 volts directly for the transmitter plate circuits have also been used successfully.

Fig. 27 shows a schematic diagram of both airplane and ground stations, including many of the switching features. A master control switch having three points serves to control the power supply for the radio receivers and transmitter. In the first position, everything is "off," in the second position, the filaments of the radio receivers and the dynamotor furnishing plate supply to the receivers are energized. In this position, which is normal while in flight, the heater circuit of the quartz crystal chamber of the radio transmitter is also energized. The third position of this switch serves to energize the filaments of the radio transmitter and to start the dynamotor furnishing plate supply to the transmitter. In this position, everything is in readiness for transmission. However, no oscillations occur in the transmitter and reception is possible. In order to transmit, it is then only necessary to press a push button which starts the oscillations in the radio transmitter. In some installations this push button is located on the hand microphone. In others it is located on the "stick" so that the pilot may operate it without moving his hand. During a conversation, this button is pressed while talking and released while listening. Relays perform all of the necessary switching functions.

Owing to the very high acoustic noise level in many airplanes, it is necessary to employ a telephone trans-

mitter of a special type. Fig. 30 shows a hand type microphone which has been developed for this use. In speaking, the rubber mouthpiece is held tightly to the lips and practically all noise is excluded from the transmitter. The closed cavity into which the speaker talks is so shaped as to avoid serious distortion of the speech.

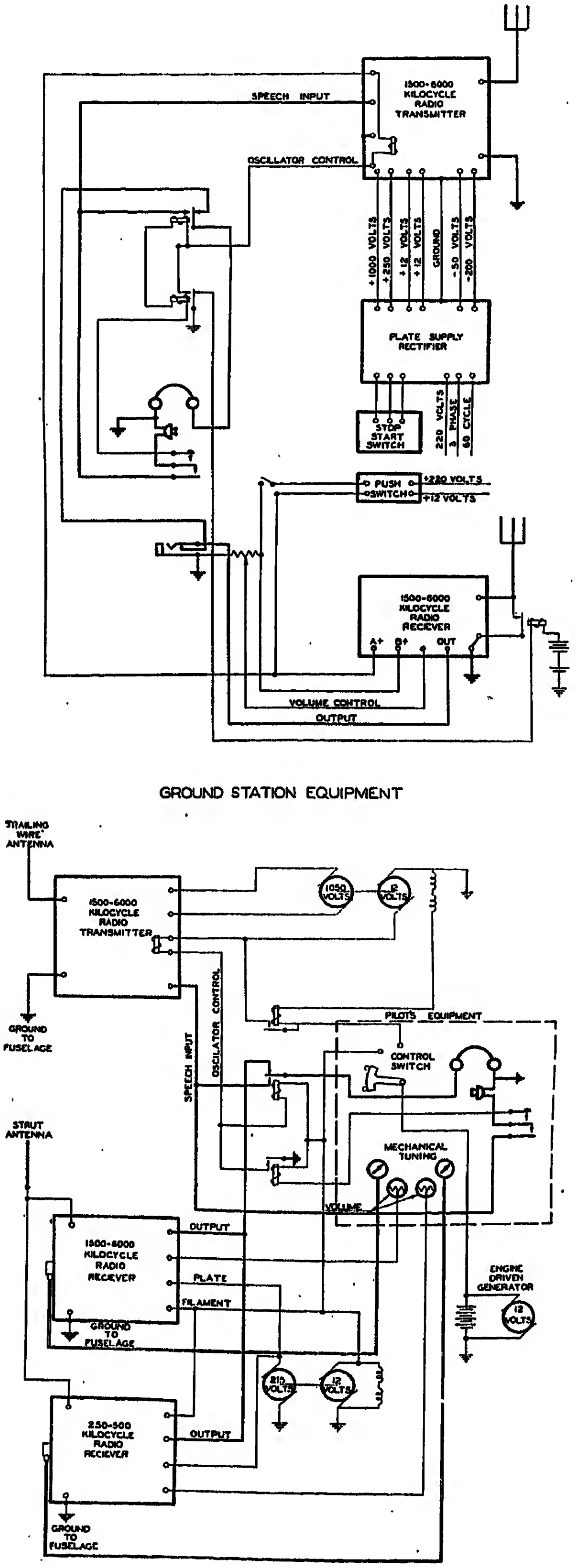

FIG. 27—DIAGRAM SHOWING EQUIPMENT OF AIRPLANE AND GROUND STATIONS FOR TWO-WAY COMMUNICATION

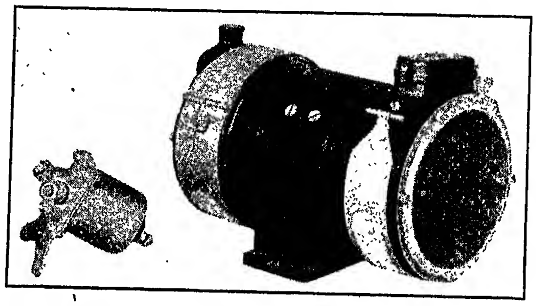

FIG. 28—DYNAMOTOR FURNISHING 1050 VOLTS SUPPLY TO THE AIRPLANE RADIO TRANSMITTER

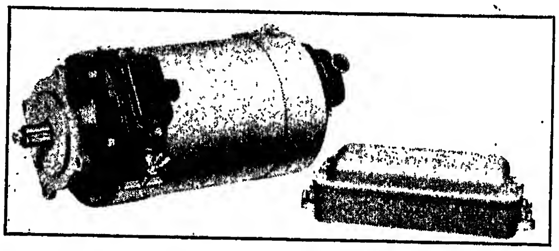

FIG. 29—ENGINE-DRIVEN 14-1050-VOLT GENERATOR FURNISHING POWER SUPPLY FOR RADIO TRANSMITTER

FIG. 30—"SILENCER" TYPE TELEPHONE TRANSMITTER FOR AIRPLANE USE

FIG. 31—SPECIAL PILOT'S TELEPHONE SET FOR USE IN MAIL PLANES

In some airplanes the noise level is not so severe and it is possible to employ transmitters with very much less shielding. Fig. 31 shows a telephone set for the use

of mail plane pilots which employs such a transmitter. The transmitter mounting is so arranged that the instrument may be dropped below the pilot's chin or turned up over his head when not in use.

Head telephone receivers similar to those employed by telephone and radio operators may be satisfactorily used in airplane work. A headset employing a small phonette type of radio receiver originally designed for the hard of hearing has been developed, however. These

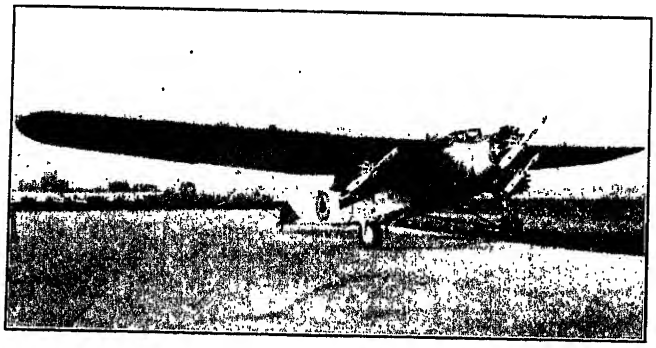

FIG. 32—NEW TRANSPORT PLANE LABORATORY

receivers, which weigh less than an ounce, are used in connection with small ear molds which are made to fit the pilot's ear.

GROUND STATION

The ground station contains the apparatus which makes up the fixed terminal of the communication link with the airplane in flight. In general, its design follows conventional radio engineering practises and for that reason this paper refers to it much more briefly than to the airplane terminal.

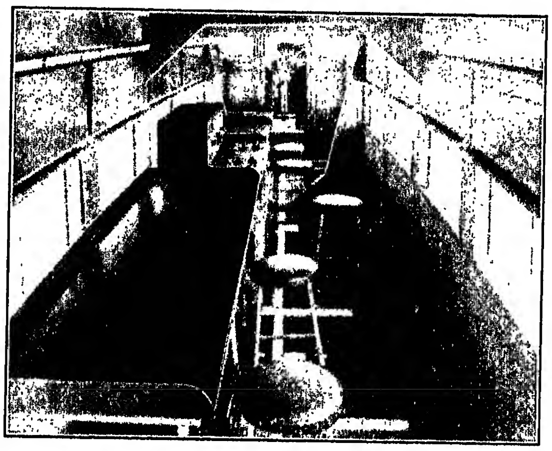

FIG. 33—INTERIOR OF NEW TRANSPORT PLANE

The radio receiver is practically identical in fundamental design with the high-frequency receiver for airplane use, which has already been described. A special radio telephone transmitter has been developed for ground stations. This transmitter has a carrier power output of 400 watts and is capable of complete modulation. A single radiation-cooled vacuum tube is employed in its output stage. It may be adjusted to any frequency from 1500 to 6000 kilocycles and is provided with crystal frequency control similar to that employed in the airplane radio transmitter. The power supply for the plate circuit of this transmitter is ordinarily obtained from a three-phase rectifier employing tubes of the hot-cathode, mercury-vapor type.

CONCLUSION

This paper has outlined experimental results fundamental to airplane communication and described the system of apparatus resulting from the associated development work. This apparatus is just becoming available and regular transport planes of several lines will shortly be equipped with it. The Bell Telephone Laboratories has recently added to its smaller ship, a large transport plane (Figs. 32 and 33), fitted as an air laboratory, in order that its future studies may proceed with enlarged scope. This is an all-metal, tri-motored ship. The future holds many interesting problems in the study of communication as an aid to travel and commerce by air. The work described here is a beginning to which future engineering will add many interesting records.

Discussion

S. M. Hamill: I should like to ask what form of voltage control is used on the generators to counteract the varying speed of the drive.

S. C. Hooper: (communicated after adjournment) The problem of air transport communication should include provision that the weather and beacon services are so uniform that any plane equipped with radio will find the system similar in any section of the country, and the listening frequencies of ground stations always the same, so that any plane, whether it be transport, private, or government, would at all times be able to avail itself of weather data, bearings, beacon services, and terminal communications without the necessity of consulting documents and data.

Also, it should be borne in mind that direction findings for numerous airports not on the transport routes is going to be an important matter for individual planes desiring to make port in thick weather. Experience in the Navy indicates that every plane must carry a "homing device," *i. e.*, a radio compass, for this purpose. The carrier waves of broadcasting stations, scattered as they are throughout the country, offer a fine opportunity of taking bearings from a plane, provided the plane is equipped with a "homing device." It must also be borne in mind, in this connection, that satisfactory radio bearings cannot be obtained at frequencies much higher than 1000 kilocycles.

F. M. Ryan: The generators are directly geared to the airplane engine and are, of course, subject to wide variation in speed. In commercial transport work that speed is not as wide as in military work, but it may be as large as two to one in some cases. Such regulation as Mr. Hamill mentioned is very important. It is usually accomplished with a regulator not unlike the Tyrrill regulators used in power practise. That is a relay which intermittently opens and closes part of the field current. Ordinarily the voltage may be held within a few per cent.

Another type of power supply for the transmitter as well as the receiver is, of course, the wind-driven generator. In that case the fan is arranged with a blade the pitch of which tends to change with the speed and thereby is made self-regulating. These hold within about 2 per cent in speed. If the machine is suitably compounded, the voltage will be satisfactory under varying load conditions.

The Future of Higher Steam Pressures
in Steam Electric Generating Stations

BY IRVING E. MOULTROP[1]
Fellow, A. I. E. E.

Synopsis.—Construction and operating experience has shown that a large part of the theoretically possible gains in efficiency due to higher steam pressures has been obtained in practise.

What are the future possibilities of higher pressures?

The biggest problem before station designers today is to reduce the cost of construction per unit of capacity. Some engineers have suggested that we should build cheaper and less economical stations. This is an unsatisfactory answer to the problem. The proper answer is to maintain the high standards of efficiency that have been established and reduce the cost of construction by intensive study and better design. Better engineering in the future is the answer to the problem.

By the use of large turbine generator units and large steam generating units, the unit cost of construction can be reduced materially. The present practise of installing several boilers to serve one turbine generator increases the cost of construction. The use of large steam generating and turbine generator units will reduce the unit cost of high-pressure stations more than it will reduce the unit cost of normal pressure stations.

If the steam generating units match the turbine generator units in capacity, we can design for unit construction. This unit construction will not only reduce the cost of construction but will also simplify operation.

* * * * *

MUCH has been written about the present state of development in the use of higher steam pressures in steam electric generating stations. The plants in service and under construction have been discussed at length in the technical press, and it would be useless to endeavor to present to you a detailed picture of what has been accomplished. It is sufficient to say that a large part of the theoretically possible gain in efficiency has been obtained in practise, and there is every reason to believe that we will, in the near future, obtain as near the theoretical efficiencies possible as we have in stations designed for more moderate operating pressures.

It would appear to be of more use to attempt to take stock and discuss the future possibilities of higher pressures.

In meeting our every-day problems, we are prone to see only the immediate job before us and to lose sight of the broad economic problem with which we are dealing. It is becoming more and more necessary to keep the broad problem before us continually and to so conduct our every-day work that it will fit into the larger picture to the best advantage.

A résumé of the accomplishments of the past is helpful only in focusing our attention on the possibilities of the future. The work done so far in raising the operating steam pressure has produced results that are very satisfactory. They are satisfying principally, however, because they indicate that we have made progress and lead us to believe that we will continue to do so in the future.

Looking back at the development of the steam electric generating station since Mr. Edison started the Pearl Street Station in New York City, what can we learn of particular moment to guide us in the design of new stations?

1. Chief Engineer, The Edison Electric Illuminating Company of Boston, Boston, Mass.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

Many things have been accomplished and the best of these should be incorporated in the new installations that we are about to make.

Many costly mistakes have been made and these should not be repeated, for while it is excusable to err, to repeat an engineering error is an economic waste.

Let us select for discussion a few salient points of a general nature, and let us confine ourselves to those points that need to be kept constantly before us in our new designs.

First and foremost, we find that in the past we have so designed our stations that the fixed charges on the cost of construction are several times the combined cost of fuel, maintenance, and operating labor. It is therefore apparent that by attention to this fact we can make the largest saving in the cost of generating electrical energy. This problem undoubtedly takes precedence over all others before the industry today. What is the answer?

Some engineers have gone so far as to recommend that we forget our efforts for higher thermal efficiencies and build cheaper and less economical generating stations. That is not a satisfactory answer. It is not right that we should cast aside the accomplishments of the past, for the facts of the case prove that those accomplishments have resulted in reducing the cost of supplying electric service.

What we should do is to maintain the higher efficiencies that have been obtained and at the same time reduce the cost of construction by more intensive study and better design.

Better engineering in the future is the answer to our problem.

We are doing better engineering today than in the past because of the accumulated engineering data available and because of the extensive research work of the past few years. Better engineering will result in more economical designs, more economical use of the materials of construction, more economical production,

greater simplicity and ease of operation, and probably higher thermal efficiencies.

As a matter of fact, we are fortunately trapped by circumstances for our own good. We cannot afford to build stations today of the same design as those built a few years ago. A careful study will show that if our fuel cost us nothing we could not afford to build stations with as low thermal efficiencies as were built ten or fifteen years ago. No! The answer to the problem is not to take a backward step but to go forward. By better design we can maintain the high standards of efficiency and at the same time reduce the cost of construction and the fixed charge item in the cost of supplying electric service to our customers.

As electrical systems have grown in size, the capacity of the prime movers and generators has grown likewise. The use of larger turbine generator units, when intelligently used, has reduced the unit cost of generating stations irrespective of the operating pressure. However, it appears from the facts available at this time that the use of large turbine generator units favors the higher pressure stations more than it does those designed for more moderate pressures. Today a 50,000-kw. unit for 1200-lb. pressure costs somewhat more than one designed for 350-lb. pressure, but a 125,000-kw. unit costs about the same whether designed for 1200- or 350-lb. pressure.

It would therefore appear advisable in high pressure stations to install as large-sized turbine generator units as practical from the operating standpoint. The recent designs of turbines that give practically the same economy over wide ranges of load have made it advisable today to use larger units than would have been advisable a few years ago for the same system load conditions.

Interconnections of electric systems also permit the installation of larger turbine generator units than would be advisable without interconnections. This factor should not be lost sight of if the fullest advantages are to be obtained by interconnections.

In the past, the size of our steam generating units in our stations has always lagged behind the size of our turbine generator units. From three to five boilers are often installed to serve one turbine generator with a resultant large increase in the unit cost of our boiler plants when compared with a design in which the steam generating unit matches the size of the turbine generator unit.

There seems to be no basic reason why the steam generating units should not match the turbine generator units in reliability. Already steam generating units have been operated with availability factors in excess of 90 per cent. If this performance can be matched consistently, there seems to be no reason why one steam generating unit should not supply all of the steam for operating one turbine generator unit. We can then have unit construction, one boiler feed pump, one boiler, one turbine, one condenser, one circulating water pump, and one auxiliary power supply. A reasonable number of cross-connections will insure continuity of service and will reduce the unit cost of spare equipment.

It is also true that this better balance between the size of steam generating units and turbine generator units is desirable irrespective of the operating pressure employed, but the accomplishment of the proper balance will make a greater reduction in the unit cost of the high pressure stations because of the higher unit cost of high pressure boiler plant equipment.

The argument of "the larger the unit, the lower the unit cost" carries throughout the station, for it applies to station structures, piping, and auxiliaries. It likewise applies to transmission lines, substations, and distribution systems right up to the customer's meters. The basic reason for this is the fact that the larger units permit the most economical use of the materials of construction, labor, and supervision.

Construction experience has very definitely shown that the size of the unit has a great deal to do with the comparative cost between high-pressure and moderate pressure installations. Undoubtedly a 5000- kw. 1200-lb. installation would cost more per kilowatt than one for 350 lb., while for much larger units there appears to be little if any difference in unit cost. This is undoubtedly the reason why comparative studies for small plants for industrials usually show that the normal pressure installation is the cheaper, all factors considered.

The recent A. S. M. E. Steam Table Research Committee's publication of the Total Heat Entropy Diagram extended to 3500 lb. per sq. in. and 1000 deg. fahr. total steam temperature has very clearly pointed out that for every steam temperature there is a theoretically economical pressure. The higher the temperature, the higher the economical pressure. For a temperature of 750 deg. fahr. and the regenerative reheat cycle, the economical pressure is in the neighborhood of 1400 lb. per sq. in. In other words, the steam temperature is in reality the governing factor.

Already the Detroit Edison Company has decided to lead the way in an attempt to raise the operating steam temperature to 1000 deg. fahr. They have purchased a turbine generator to operate with steam at moderate pressure at this temperature for their new Delray Station.

As the difficulties with the higher temperatures are worked out, the higher temperatures will be combined with higher pressures and there is a possibility that we will be faced with the necessity of raising operating pressures even higher than 1400 lb.

The development of equipment suitable for utilizing steam at 1000 deg. fahr. will result in justifying the use of higher pressures without reheat, and who can say that with reheat 3200 lb. per sq. in. will not be justified?

If the time comes when pressures considerably in excess of 1400 lb. are justified, we must depart radically from our present designs of boilers. We must abandon

thermal circulation in boilers and water-cooled furnace walls and adopt forced circulation. Just because we cannot at once reconcile our minds to such a radical departure in design is no reason for our feeling that there is nothing in the idea before it has been given a thorough trial. Some European engineers believe that forced circulation is advisable for pressures as low as 1500 lb.

The European trend is distinctly toward higher steam temperatures at moderate pressures because the engineers over there believe that the unit cost of high pressure equipment is too great to be justified by the fuel savings to be obtained by its use. On the other hand, in America the trend is just the other way; *i. e.*, higher pressures at moderate temperatures. It is the opinion of American engineers that higher temperatures call for the use of alloy steels and the proper alloys are not available today at prices that make their use profitable.

There is no doubt that many engineers on both sides of the Atlantic Ocean are fully alive to the proper relation between pressures and temperatures, and you can find many instances where certain companies are going far ahead of the general trend. Two noteworthy examples of this are the Detroit Edison Company's purchase of 1000 deg. fahr. equipment, and the recent purchase of a 300,000 lb. per hr., 3200 lb. per sq. in. Benson boiler for the Langerbrugge Station in Belgium.

We have been told on many occasions that the laws of diminishing returns will preclude going much higher in pressures or temperatures, and yet both in America and Europe engineers are going ahead and accomplishing results with higher pressures and temperatures that may force a revision or a reinterpretation of that law of diminishing returns. It is indeed very dangerous to draw definite conclusions from trends; it is wiser to watch the accomplishments of the pioneers.

The experience thus far gained in the construction and operation of high pressure and high temperature stations has very clearly shown that the design and operation calls for engineering talent of the highest type. Designs and construction details must be worked out with the greatest care or otherwise the cost of construction will increase to a point where the fixed charges will offset the savings in fuel. On the other hand, if the proper skill is exercised there does not appear to be any additional capital burden and the greater economy pays a handsome dividend on the effort expended. The argument that greater skill is required is no valid reason for refraining from using the most economical equipment any more than a merchant should refuse to enlarge his business for fear that the larger and more profitable business will require more careful planning and attention.

Construction experience has shown also that high-pressure stations need not be confined to base load operation. Since they can be built for practically the same unit cost as low-pressure stations, they impose no additional capital burden and can be justified for supplying the normal load of the system. This fact will undoubtedly greatly increase the use of higher pressures in the future because it is seldom practical to operate a generating station as a base load station for a long period of years.

Just as the hand-fired grate for large boilers has passed into the discard with the development of efficient automatic fuel burning equipment, so have "rule of thumb" design, construction, and operating practises passed on. Brains instead of brawn rule today.

The Fault Ground Bus

Its Use and Design in Brunot Island Switch House of Duquesne Light Company

BY R. M. STANLEY[1] and F. C. HORNIBROOK[2]
Fellow, A. I. E. E. Non-Member

Synopsis.—*This paper describes the ground protection in the Brunot Island switch house of the Duquesne Light Company at Pittsburgh, Pa. This switch house constructed on the vertical isolated-phase plan, is divided structurally into several completely insulated sections.*

The well known fault ground bus system of protection is applied and made effective by the special features of construction not heretofore used.

Details of building construction and of fault ground bus application are given.

Arrangements for heating, ventilating, and lighting the buildings are such as not to interfere with phase isolation and insulation.

Oil circuit breaker mechanisms are insulated where necessary to maintain the building subdivision into insulated sections.

The fault ground bus location, connections, and special details of construction are outlined. Preliminary tests, relay settings, and operating results are given.

* * * * *

INTRODUCTION

THE Brunot Island switch house constitutes the largest 12-kv. switching center on the Duquesne Light Company's System in Pittsburgh.

Greater Pittsburgh and vicinity are supplied with electric energy from two principal generating stations, Colfax and Brunot Island.

Colfax station of 280,000-kw. capacity is located on the Allegheny River about 14 miles from the down town district.

Brunot Island station, located on an island in the Ohio River about four miles from the down town district, has a total capacity of 110,000 kw. Adjacent to this station there is now under construction a new generating station known as the James H. Reed station to contain initially one 60,000-kw., 75,000-kv-a. steam turbo generator with space for a second similar unit in present building. Ultimate extension is possible for several more units. A large part of the district supplied by the Duquesne Light Company system is enclosed by a 66-kv. transmission loop, the north branch extending from Colfax Station around the north and west sides of the city and the south branch from Colfax station around the east and south sides of the city, merging at Brunot Island switch house. Power is supplied, at present, from this switching center mainly by means of 12-kv. underground cables carried from the island across two channels of the Ohio River to various step-down switching centers supplying industrial customers' substations, distribution substations, and low-voltage networks. Approximately half of the total system load is found within a radius of about four miles from Brunot Island.

The Brunot Island switch house, completed and put in operation in 1928, replaced a switch house which was outgrown as regards capacity and adequacy of switchgear.

In the new 12-kv. switch house the connections include a main bus, a transfer bus, and a synchronizing bus. The main and transfer buses are sectionalized and the grouping of generators, feeders, and transmission line circuits is such that a bus section can be retired without impairment of service or overload of connections. The main connections are shown in Fig.

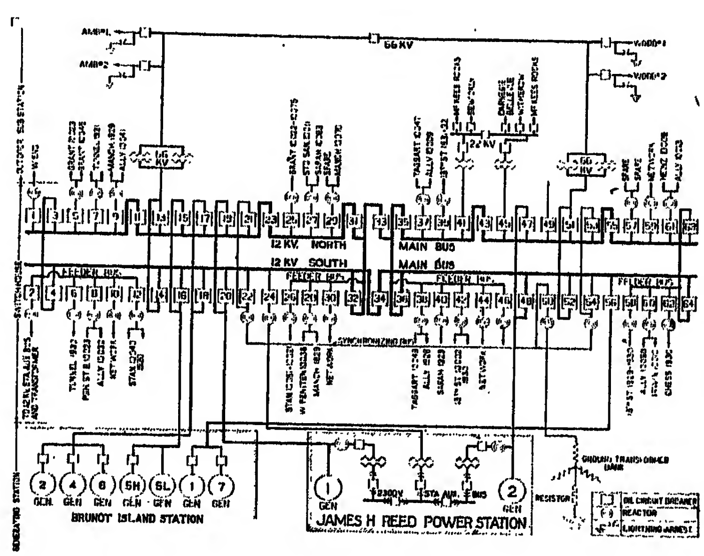

FIG. 1—ONE-LINE DIAGRAM OF MAIN CONNECTIONS

1, One-Line Diagram. With this provision for the retirement of portions of the equipment by the flexibility of the switching scheme, ordinary operating conditions are met. But abnormal operation due to the eventual breakdown of insulation at some point is also considered in the switch house design. To that end the isolation and insulation of phases is maintained in an unusual degree. This condition is made effective by the introduction of certain features not hitherto used in the design of the structures, and arrangement of equipment.

1. Byllesby Engineering & Management Corp., Chicago, Ill.
2. Byllesby Engineering & Management Corp., Pittsburgh, Pa.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

29-159

Switch House Arrangement

The switch house is a five-floor structure 225 ft. long by 90 ft. high by 40 ft. wide with vertical isolated-phase arrangement, each of the three upper floors containing one of the phases of the switchgear bus structure. (See Figs. 1, 2, and 3.) There are 64 oil circuit breakers, mounted on the phase floors, along with the disconnecting switches. Each oil circuit breaker is made up of three single pole elements, mounted vertically in line, one element on each phase floor. The generator, transformer, and bus section oil circuit breakers have a so-called short-circuiting switch (secondary contacts of the breaker) mounted directly above the breaker. For the feeder oil circuit breakers this space is occupied by the single-phase feeder reactors.

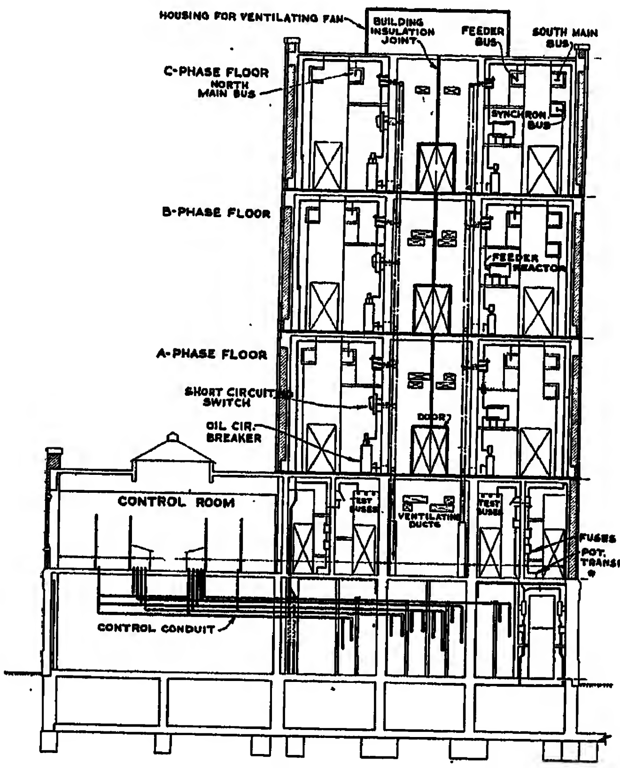

Fig. 2—Side View of Switch House Apparatus

Each oil circuit breaker with its disconnecting switches is operated as a unit from a motor-operated mechanism located on the floor below the lowest phase floor. On the same floor with the oil circuit breaker operating mechanism are concrete cell structures housing instrument transformers, line disconnect switches, and disconnect switches for transferring 12-kv. feeder cables to a 30-kv., 25-cycle test bus and special disconnecting switches for testing 12-kv. feeder cables are also located on this floor. The ground floor is used for conduit for control wiring between the switch house and the power station.

The switch house has a two-floor annex, with the control room on the second floor and the 12-kv. feeder testing equipment, 250-volt control batteries, and battery charging sets on the first floor.

The testing equipment includes a motor-generator set with a testing transformer giving a 25-cycle test voltage up to 30,000 volts.

Below the phase floors the circuit arrangement is the usual three-phase grouping with barriers separating the phases. Single-phase leads coming from each of the three-phase floors are brought together on the second floor of the switch house.

Below the ground floor there is a cable vault under the entire building, which provides the desired flexibility, for routing the outgoing and incoming cables.

Electrical Connections

There are three main buses in the switch house, one running the full length of the building on the north side and divided into six sections designated the North bus; one running the full length of the building on the south side and divided into two sections designated the South, or Transfer bus; and a synchronizing bus which parallels the transfer bus on the south side of the building. (Fig. 1.) Three sections of the North bus and one section of the Transfer bus, directly opposite, comprise one of two switching units.

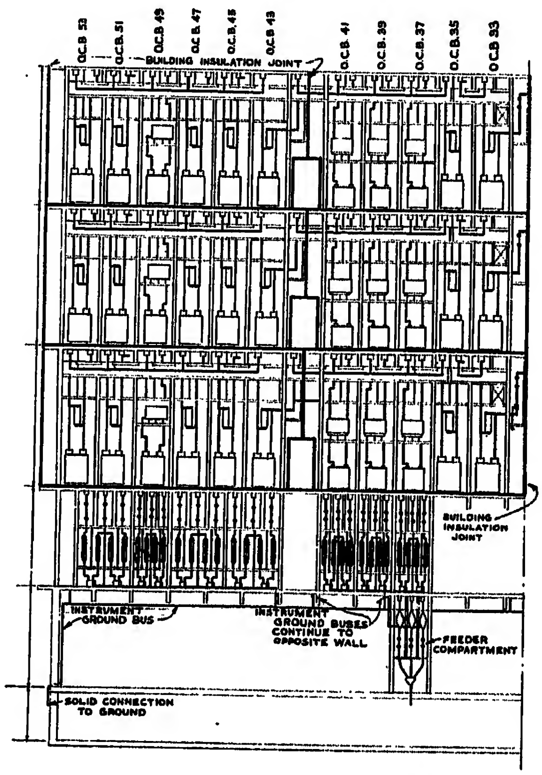

Fig. 3—Switchgear Bus Structure

A switching unit consists of a number of breakers connected to a generator bus which is the center unit of the North bus just described. On each end of this generator bus is a feeder bus to which are connected three or more feeder breakers. Opposite these feeder sections on the south side of the building are short

sections of the feeder bus connected to the feeder sections mentioned above and also connected to the Transfer bus. The Transfer bus is also connected in

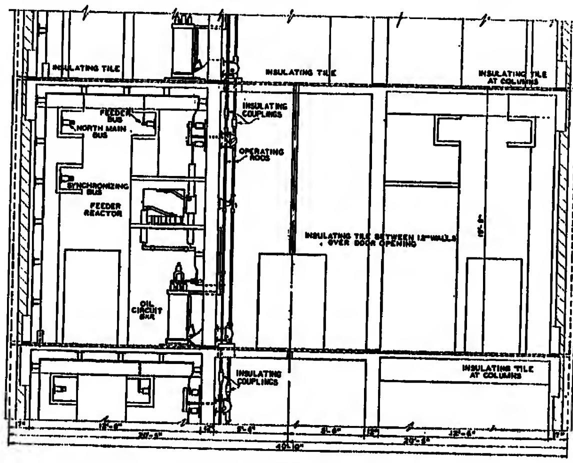

Fig. 4—Showing Insulation of Sections of Building

general to the same circuits to which the generator buses are connected. Typically, each generator section contains switching for one or more generators

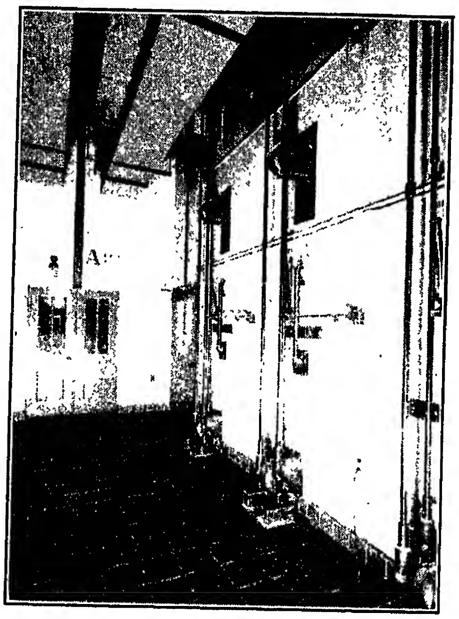

Fig. 5—Building Splits

Center or mechanism aisle on "A" phase floor showing longitudinal and cross-wise building splits. These splits are located at the black lines shown over the doors. Ventilating ducts are shown above with ebony asbestos insulating splits to maintain isolation between phase sections. The mycalex insulating couplings in the oil circuit breaker mechanism rods can be seen on the bell cranks at floor level. For each set of three rods, the rod on the right operates the breaker and short-circuiting switch while the two rods on the left operate the disconnect switches.

Rods operate bell crank mechanisms enclosed in vapor-proof cast iron covers. Above these may also be seen gas vents from oil circuit breakers and part of mechanism which mechanically interlocks protective doors of oil circuit breaker cells.

Note that no conduit crosses a building split.

which are also connected to the transfer bus opposite. This generating bus also contains typically one or more transformer circuits and a synchronizing circuit and these circuits are also connected to the transfer bus by circuit breakers.

Insulation of Sections of the Building

In order to maintain phase insulation, the three upper floors, each containing one phase of the bus structure, are insulated from each other and from ground. This is accomplished by placing on each floor a layer of standard hard-burned floor tile of high electrical and compressive strength, using insulating compound instead of mortar in the joints. (Fig. 4.) The steel reinforcing in the concrete structure is not continuous, but tile underlies all reinforced concrete walls, columns, and barriers. Besides this horizontal insulation of the phase floors, the building is further subdivided as follows:

With the purpose of using the fault ground bus system of protection the building is split vertically with insulating joints to correspond with the sectionalizing of the main bus. One vertical split follows the longitudinal axis of the building as indicated in Figs. 2, 5, and 6. Crosswise vertical splits divide the building into six sections lengthwise, corresponding to the six sections of the North bus, as shown typically in Fig. 4. The building is thus divided on each phase floor into twelve insulated sections.

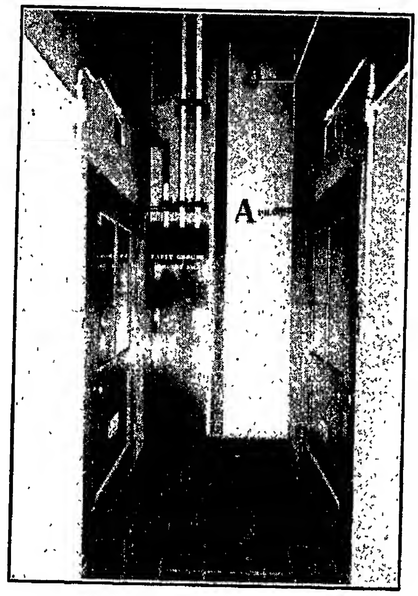

Fig. 6—Building Split and Risers on "A" Phase Floors

Passage way between phase sections on "A" phase floor showing insulating building split on back wall. This also shows the risers to the phase floors of one fault ground circuit with "A" phase connection dropping off and being carried on bar copper.

The building construction, therefore, is of reinforced concrete consisting of phase rooms built as though complete boxes were set one upon another, each comprising sides, top, and bottom, so that a breakdown of electrical apparatus or connections must be confined to the inside of this box or room.

Heating and Ventilating in Relation to Phase Isolation

The entire building is heated and ventilated by the indirect method. Steam is piped from the adjacent steam station to the basement of the building. Runs of piping to the roof in the stairwells at the front of the building are insulated from the phase rooms by inserting insulating couplings in both the main header and in the condensate return lines. In addition the pipes are supported by insulated brackets.

Two 13,000 cu. ft. per minute fans driven by 7.5-hp. motors are located under housings on the roof, one at each end of the building. Steam is supplied to heating coils and air is forced past these coils down through sheet metal ducts to the phase rooms. Paralleling these ducts are exhaust ducts which take the air from the room again, this being exhausted by other fans located on the roof. Dampers are provided to regulate the flow of air and to balance the system. Where ducts pass from one phase room to another on the same floor or to another floor, the metal duct is not continuous but has insulating joints of ebony asbestos so that the phase isolation is preserved.

Lighting in Relation to Phase Isolation

Lighting of phase rooms is accomplished in the following manner:

At the end of each phase room are recesses in the concrete wall at a suitable height from the floor containing two 100-watt lamps. (Fig. 7.) In front of these lamps is a heavy sheet of glass which diffuses the light and illuminates the phase rooms very efficiently. The supply circuits to these lamps as well as to other lights in the center aisles, etc., are brought from one to one ratio insulating transformers of which there is one for each of the 36 insulated phase rooms. (Fig. 8.) Conduit carrying feed to the insulating transformers from lighting cabinets on A phase floor is not continuous but has sections of micarta tubing of the same size as the conduit when passing between phase floors. No lighting circuits cross from one insulated phase room to another on the same floor. The insulation interposed on wires and on transformer is sufficient to prevent the flow of fault ground current to ground through the lighting system and the liability of damage to station lighting circuits is eliminated.

Fig. 7—Phase Section Showing Lights

Phase section showing lighting fixture at end of room and opening to exhaust ventilating duct directly above. Oil circuit breakers are in the compartments to the left and bus runs in the flues on the right

Fig. 8—Insulating Light Transformer

Center or mechanism aisle showing lighting cabinet on "A" phase floor and insulating lighting transformer, of which there is one for each of the 36 insulated building sections. Note that conduit to the lighting cabinets from the floor below has sections of micarta tubing through the floor to prevent grounding of the phase section. The mycalex insulating couplings in the oil circuit breaker operating rods can also be seen

Switchboard Control and Instrument Circuits in Relation to Phase Isolation

Oil circuit breaker control wiring is brought to the motor mechanism located on the floor below the lowest phase floor so that interference with oil circuit breaker operation cannot result from failure on the phase floors.

Secondary circuits of current transformers in the buses between sections on A phase floor are insulated before reaching the switchboard instruments by means of a 5-ampere, 15,000-volt current transformer of one to one ratio located just below the phase floor. (Fig. 9.) The frame and secondary winding of the bus tie current transformer are connected to the fault ground bus (Fig. 10), while the frame and secondary winding of the isolating current transformer are connected to the instrument ground bus. By use of this isolating current transformer, fault ground current resulting from breakdown of apparatus or failure of insulation on the lowest phase floor cannot reach the control board.

The same protective scheme is used in connection with current transformers in the synchronizing reactor circuits and can be applied to other circuits should it later prove desirable. However, current transformer failures have been so rare that it seems unnecessary to make this general extension of the fault ground system.

Switchgear in Relation to Phase Isolation

As stated before, the single pole units of the three-phase breaker equipments are mounted vertically in

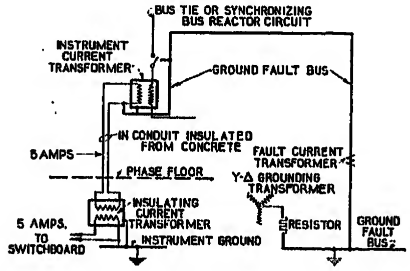

Fig. 9—Insulation of Circuits by Use of One-to-one Ratio Transformers

line on the three-phase floors and are operated from a motor-mechanism located below the lowest phase floor.

The rods which operate the breakers, disconnect switches, and short circuiting switches have insulating micalex couplings for maintaining phase isolation. The distance between mechanisms, rods, walls, etc., and the insulating couplings is such that an operator is not liable to touch any part of equipment belonging to one phase room while standing on the floor belonging to another phase room.

Switchgear Interlocks and Operation

Mechanical interlocking of oil circuit breakers, disconnecting switches, test switches, and doors in front of compartments was adopted in preference to any other form of interlocking. Line disconnecting switches or test switches cannot be operated until the oil circuit breaker is open. Doors in front of oil circuit breaker cells cannot be opened, if the oil circuit breaker or disconnecting switches are closed.

Certain interlocks are inherent in the main control of the switchgear. In the closing operation a charging control switch causes a motor in the operating mechanism to compress a pair of springs and at the same time the disconnecting switches are closed. The main control switch is then operated, a spring is released, and the oil circuit breaker is closed. The opening operation, using only the main control switch, releases the other spring previously compressed, opens the circuit breaker and after that the disconnecting switches.

When an oil circuit breaker is tripped out by relays during a system disturbance, the oil circuit breaker only is opened and the disconnecting switches remain closed until the control switch is turned to the opening position. This feature avoids the possibility of rupturing a heavy current on the contacts of the disconnecting switches.

Ground Protection

Ground faults in generators and their auxiliary transformers operate through differential relays to isolate the equipment affected. Power transformer banks including high-tension buses are also protected by differential relays. Feeder grounds are taken care of by the usual ground relays.

A grounding transformer bank of 10,000-kv-a. capacity is connected, in star, to the 12-kv. bus and is provided with a grounding resistor of 15 ohms. The secondaries of this bank are in closed delta. Current transformers in the ground connection of this bank operate high-speed recording instruments and give an alarm in the event of an appreciable flow of ground current.

Fault Ground Bus System

For the protection against insulator breakdown in the 12-kv. bus and its connections, two general

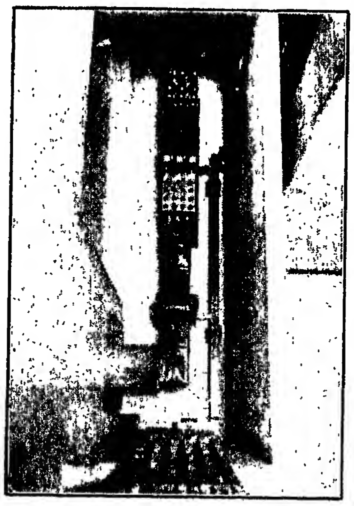

Fig. 10—5000-Ampere Disconnecting Switch Compartment

5000-ampere disconnecting switch in compartment to the right of the oil circuit breaker compartment, so located as to prevent copper or other vapor from communicating to next main or fault bus section on the right from sections on left; (part of isolation scheme). The insulated fault ground circuit is shown passing through the left-hand wall into the oil circuit breaker compartment and to the right into an adjacent bus section. One tap fastens to the disconnecting switch base which is insulated from the building by means of a sheet of micarta and by the use of micarta bushings where the mounting bolts pass through the base. Another tap is connected to the frame and secondary winding of the bus section current transformer. This transformer is supported by the bus and is not fastened to the concrete. Bus section current transformers are located in "A" phase only.

Note sheet of ebony asbestos at right to prevent flashover to concrete

schemes may be applied. The application of bus differential protection as used in certain of the Duquesne Light Company substations would have involved the use of a large number of additional current transformers, introducing difficulties in the matter of space requirements. Further, phase isolation as previously described would have become more difficult with the introduction

of additional conduit runs. Therefore, the fault ground bus system of protection was chosen.

Switch house faults may include failure of switchgear during normal or abnormal operation, failure of connected equipment such as reactors, and the break-

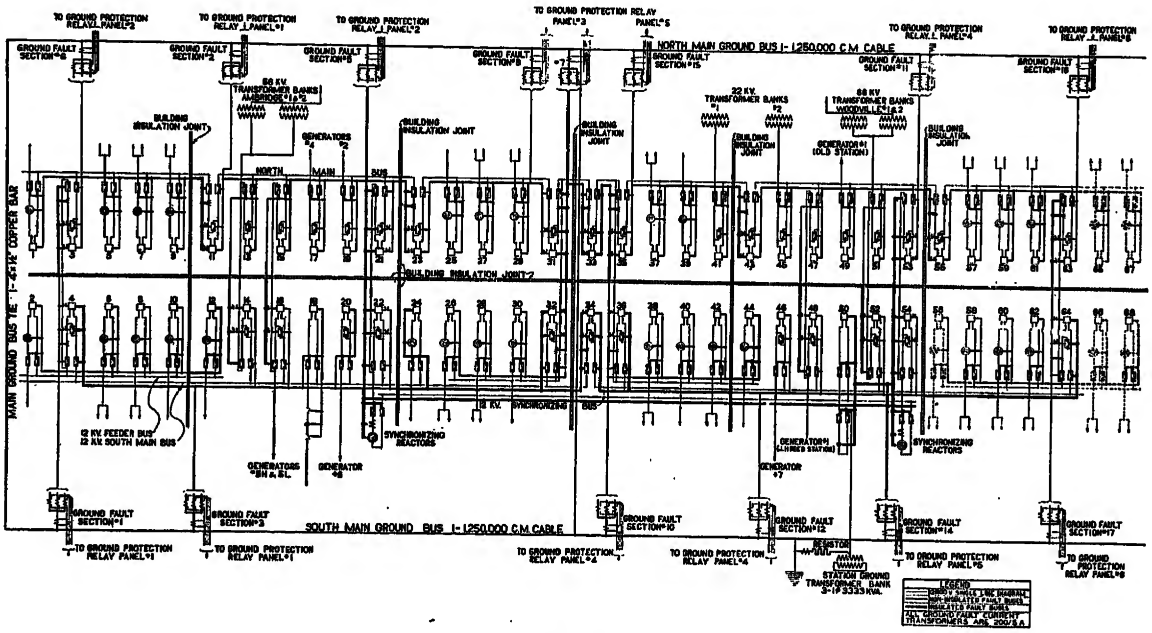

FIG. 11—DIAGRAM OF FAULT CIRCUITS

down of insulators supporting buses or connected circuits. The effect of the failures enumerated is lessened by the isolation of phases and due to the insulation between phases and sections. These breakdowns will cause phase to ground faults limited to a single-phase floor and a single room.

DESCRIPTION OF FAULT GROUND BUS

For each of the twelve insulated building sections,

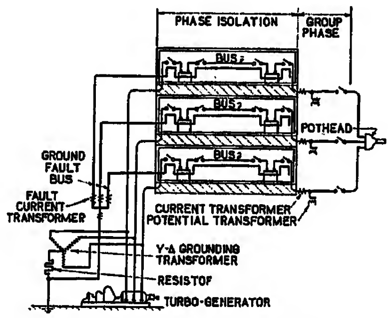

FIG. 12—PHASE INSULATION OF FAULT CIRCUIT

there is one uninsulated fault ground circuit. The fault ground bus consists partly of 2-inch by ¼-inch copper bar closely paralleling the main connections and connected to certain non-current carrying parts of switchgear, and partly of insulated 1,250,000 cir. mils copper cable. Considering one switching unit alone there is one fault circuit for the main or generator bus on the north side of the building, one for each of the two feeder sections on the north side of the building, one for the transfer bus on the south side of the building and one for each of the two feeder sections on the south side of the building. (Figs. 11 and 12.) Each phase of a particular fault circuit is insulated beyond the point where connection is made to the equipment and the three phases are brought to a common connection below the lowest phase floor after passing through

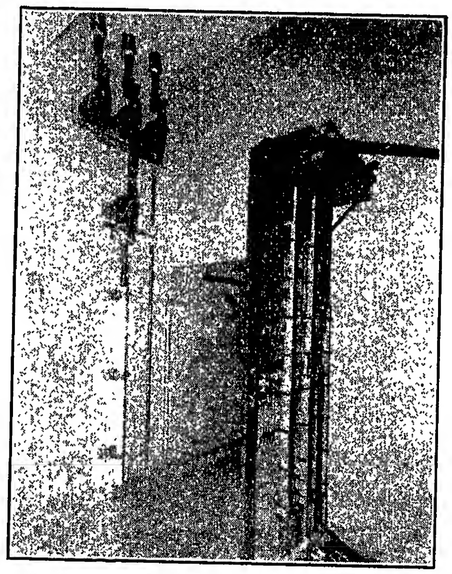

FIG. 13—FAULT PANEL AND CURRENT TRANSFORMERS

Insulated copper cable risers to the three-fault ground buses in the three isolated phase rooms.
Risers and common connection to transformer ground each provided with current transformers
Relay panel with equipment for three separate fault ground bus sections

current transformers. A fourth current transformer of the same ratio as those in the separate phases is connected in the common lead to ground. (Fig. 13.)

All the metallic parts in the switchgear, in the bus supports, reactor supports, etc., which are separated from bus potential by insulators are connected to the fault ground bus by a bar of ¼ inch by two inch copper. (Figs. 14, 15, and 16.) Where a fault circuit is continued into an adjacent insulated section of the building, it passes through an insulating bushing and is mounted on insulators after crossing the insulating building split.

Two additional fault ground bus circuits which protect the synchronizing reactor circuits are mounted on insulator supports throughout and make solid connections only to equipment which has been insulated from the building construction.

All 14 fault ground bus circuits are brought together after passing through individual fault ground bus current transformers to a common fault ground bus of 1,250,000 cir. mils cable which is solidly grounded at the same point with the Star Delta 10,000-kv-a. grounding transformer bank described under Ground Protection.

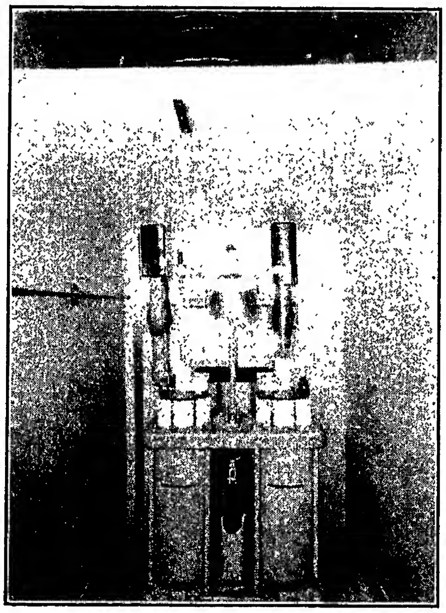

Fig. 14—600-Ampere Compartment

600-ampere oil circuit breaker compartment with reactor on shelf above. Uninsulated fault circuit is on the left making connection to the breaker, back wall contacts, and bus support insulators. Cell door interlock is shown on the left wall. It passes through the back of the compartment and attaches to pipe operating mechanism in the center aisle. Fault circuit passes up through the reactor and disconnect switch compartments and thence to bus flue

In general the fault ground bus circuits parallel the sections of the main bus and the various branch circuits from each bus section, present branch connections of each fault bus circuit being limited to regions considered as of greatest hazard. Certain bus runs where insulators are not subject to stress due to mechanical shock of adjacent operating equipment are, for the present, not provided with fault ground bus protection. Provision has been made for future extension of the fault ground bus wherever it shall prove desirable.

Fault Ground Bus Operation

In the case of a single failure from phase to ground, current will flow through the phase transformer and also through the transformer in the common connection, which, through the action of the associated overload and auxiliary multi-contact relays, will trip the breakers in the fault section. For complete protection in this class of failure there would be required only one current transformer in the common ground connection.

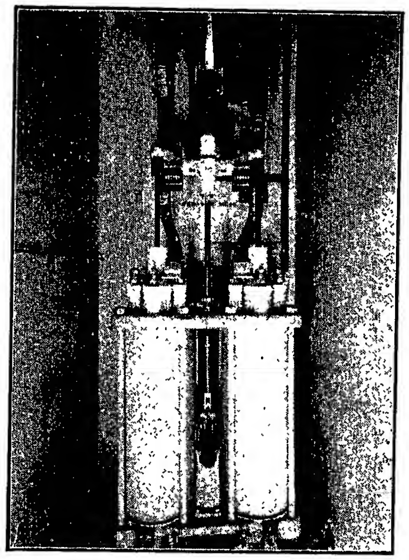

Fig. 15—2000-Ampere Compartment

2000-ampere oil circuit breaker compartment showing uninsulated fault ground circuit on the right, and cell door interlock rod on left

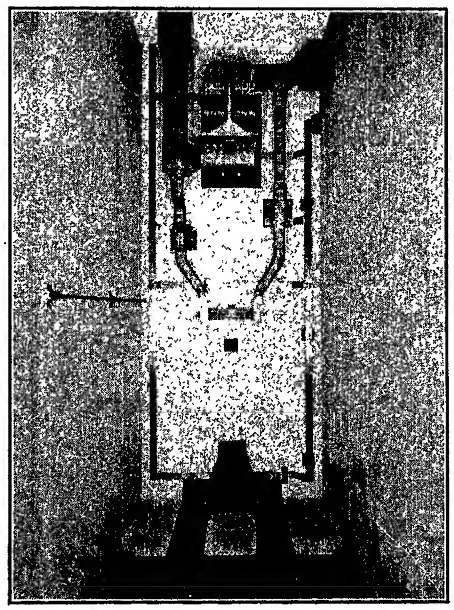

Fig. 16—Unfinished Compartment

Bus tie breaker compartment No. 55-5000 ampere. Breaker unit removed to show fault ground bus connections to breaker supports

Fault circuit to the left is uninsulated while one on right is insulated since it crosses an insulated building split to the phase section on the right. Connections of the insulated fault circuit are made to the breaker equipment through gaps which are shown supported by micarta brackets

However, in the case of two simultaneous line-to-ground failures, one of which may have resulted from the other, very little current might flow through the common ground connection and the action might have to result largely from current in the individual phases of the fault ground circuit.

Fault Ground Bus Overlapping Protection

In the case of tie breakers between two sections of a bus, provision has been made for clearing the fault from either side of the tie breaker since the fault may occur from either section to the tank of this breaker. It is apparent that the tank of the tie breaker should be connected to both fault circuits but to do so would destroy the selectivity. Another possible solution would be to create a third fault circuit to include the tie breaker alone, which would trip the circuits on both sides of the tie breaker. The disadvantage of such a scheme is that it might result often in tripping more breakers than necessary to clear the fault. For this reason the circuit on one side of the tie breaker is tripped through the action of time delay relays only after the first circuit has cleared itself and the fault still exists. (Fig. 17.) The time delay relays are set to operate after a delay of one second, which would give the breakers involved on instantaneous tripping sufficient time to clear. When two fault circuits are brought to a tie breaker, one only is connected solidly to the breaker, the other being connected through a gap which acts as a secondary means of clearing adjacent circuits in case of continued arcing on a tie breaker after the breaker has opened.

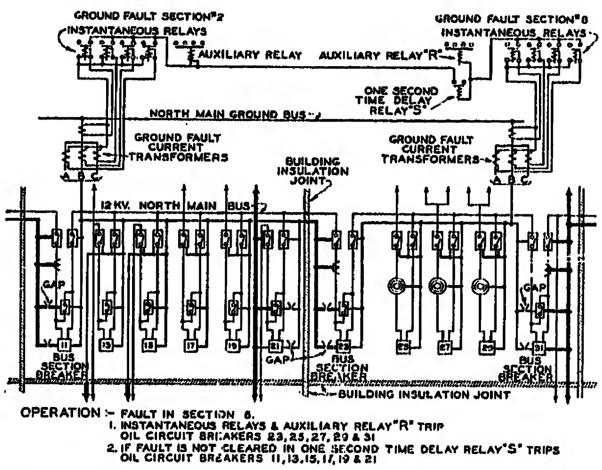

Fig. 17—Connection of Relays and Circuit Breakers

Certain disconnecting switches at the bus sections are mounted in separate cells and are protected by two fault ground systems. For instance, in the case of oil circuit breaker No. 43, the left-hand disconnecting switch is above the oil circuit breaker while the right-hand disconnecting switch is located in a compartment just outside the barrier wall at the end of the phase room. (Fig. 18.) This right-hand disconnecting switch is thus located so as to prevent a short circuit from spreading into another phase room. If the right-hand disconnecting switch should break down or become involved in trouble inside the phase room, the next adjoining bus section must be cleared. For this reason

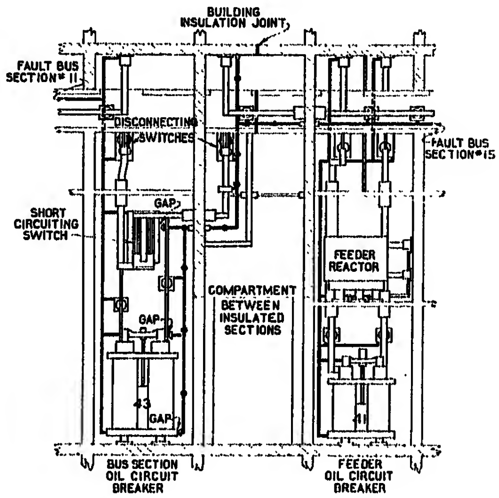

Fig. 18—Location of Disconnecting Switches

the right-hand disconnecting switch base is tied in with the fault ground bus circuit to the right. A typical arrangement indicating special gaps in the fault ground bus is shown in Fig. 19.

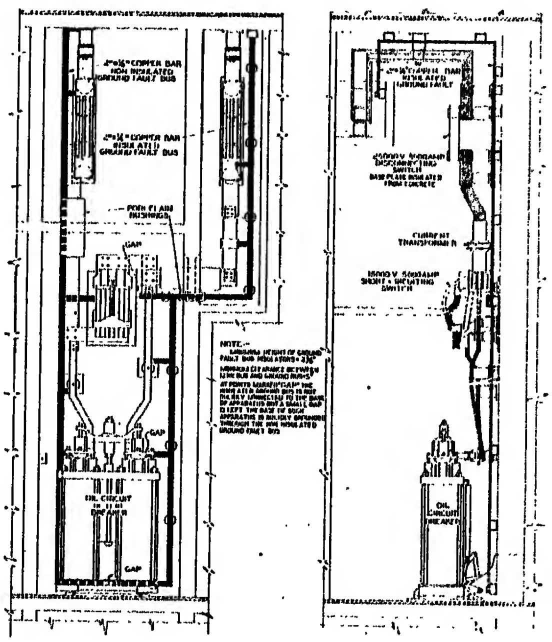

Fig. 19—Showing Special Gaps in Fault Ground Bus

The following preliminary tests were made before cutting the fault ground bus in service.

Insulation Resistance

A large portion of the fault ground system was installed after the 12-kv. circuits had been placed in service. Immediately on grounding the various fault

circuits and before making any resistance tests between phase floors or between adjacent building sections, an unexpected amount of current was found to flow in the fault circuits under normal operating conditions in the station. In the case of station or system disturbances where short circuit current flowed through sections of the station buses, currents in the fault circuits reached values sufficient to operate certain fault ground relays. It was, therefore, apparent that the protection scheme could not be used until the cause for this stray current had been determined and eliminated.

The first step was to measure insulation resistance between phase floors and between adjacent insulated building sections on the same floor. The building was considered as consisting of 36 boxes (12 per floor) insulated from adjacent boxes on the same phase floor and from adjacent phase floors. Resistance measurements could have been taken directly from the mats of reinforcing steel in the ceiling or side walls of each insulated room. Since large amounts of equipment, however, in each section are anchored into the building construction and tied together by being connected to the fault ground bus of the same section, it was assumed that resistance measurements taken from the fault ground bus itself with the ground connection broken should give more accurate results.

There is one insulated fault ground circuit for each of the 12 building sections. Portions of these circuits which cross over into adjacent sections are insulated when they cross an insulated building split, and make connections only with equipment which has been insulated from the building construction. The resistance to ground of the insulated portions of the circuit is so high as compared with that of the uninsulated portion that these connections do not appreciably affect the total resistance.

Resistance measurements were made with a direct reading "Megger" ground resistance tester having ranges of 0-3, 0-30, and 0-300 megohms. The common connection to the fault circuit under test was opened at the current transformers below the bottom or *A* phase floor and resistance measurements were taken from each phase to ground and between phases. These measurements were taken with the fault circuits in adjacent sections grounded. It was, of course, necessary to obtain an outage on all equipment connected to the circuit under test as a safety precaution and it would, therefore, have required a large portion of the station equipment out of service, if fault circuits in each adjacent building section were to be opened at the same time. By leaving the fault circuits in adjacent sections grounded, any low resistance ties between building sections, and consequently between fault circuits, would be indicated by low readings on the circuit under test. However, where it was possible to clear fault circuits in adjacent sections, this was done and resistance measurements were taken between similar phases on these adjacent circuits.

The minimum resistance of phases to ground on any uninsulated fault circuit when placed in service was 6 ohms and the maximum 25 ohms. On any one fault circuit the resistance to ground generally increased from one phase to the one above although this was not always the case, due probably to lower resistance ties to ventilating ducts, conduit, steam pipes, etc. The average resistance to ground on the top phases was higher although the maximum and minimum values varied but slightly. The resistance between adjacent phases of any one fault circuit varied from 9.5 ohms to a maximum of 30.5 ohms. The resistance of any phase to the same phase in an adjacent fault circuit varied from 11 to 41 ohms and was generally found to be higher on the top phases for any two adjacent fault circuits.

In several cases the resistance of phase to ground was zero and where such conditions were discovered it was found that circulating current existed in the fault circuit. Some of the causes for these conditions found and corrected were as follows:

1. Low-resistance ties across insulated building splits due to tie wires which were used to hold the insulating tile in place in the forms while concrete was being poured and which had not been cut when the forms were removed. These often tied the reinforcing steel mats in adjacent sections together.

2. Guy wires for construction equipment such as brick scaffolds and material elevators which were anchored through the walls or roof and consequently grounded the reinforcing steel in the particular section.

3. Conduit for ventilating motors crossing the roof split above the top or *C* phase.

4. Steam pipes passing from the heating system on the roof above the top of *C* phase down to the basement and thence to ground.

5. Defective insulation to ground of equipment connected to insulated fault circuits.

6. Foreign conducting material in the gaps on tie breakers fault ground bus connections.

When these causes for low resistance had been found and corrected, it was discovered that the circulating current in the various circuits had disappeared entirely under normal and short circuit conditions on the station and system. Tests of circuits under actual ground conditions inside the station were next made as follows:

The First Series of Tests

In this series of tests the ground current was limited to approximately 400 amperes by the 16-ohm resistor in the neutral of the station grounding transformer bank. The instantaneous relays were set for 2.5 amperes to operate on a ground current of 100 amperes. All equipment associated with the fault circuit under test on instantaneous tripping was cleared from the rest of the station and system. Ground was applied by means of a cable connected to the line side of one of the breakers involved, and to the fault ground bus

in the breaker compartment. All breakers were closed except the one selected to energize the fault which generally was not the same as that to which the ground was attached, thus providing for double protection in case of faulty operation. The fault was then energized from the 12-kv. bus by closing the breaker and all breakers involved in instantaneous tripping were tripped by action of the fault ground relays. The back-up protection of tie breakers through action of the timing relays was not tested simultaneously with the instantaneous tripping, since large additional amounts of equipment would have been required in the outages. Timing relays were tested separately without actually tripping the breakers involved with one second setting. This was found to give the breakers on instantaneous tripping sufficient time to clear as the maximum time required for the largest breakers to clear the arcing contacts was found on previous tests to be 21 cycles.

Grounds were applied as above described on each phase of each of the 12 fault circuits. For each test readings of current were taken in each phase of the circuit under test, in the neutral of each of the other fault circuits, and the ground current in the station grounding transformer bank. In the majority of the fault circuits there was no indication of current flow. This series of tests would indicate that no trouble will be expected from incorrect relay operation for grounds inside the station.

Second Series of Tests

It was uncertain, however, whether the current in other fault circuits was due to actual leakage between insulated building sections or due to induction between sections of the fault bus and the 12-kv. buses. If the latter proved to be the case, there was a possibility of incorrect relay operation under short circuit conditions outside the station where the current through certain sections of the 12-kv. buses might exceed by many times the station ground current as limited by the station ground resistor. For this reason a series of tests was run on certain of the fault circuits with grounds applied on 12-kv. circuits at substations remote from the switch house and with the station ground resistor reduced to one-fourth its normal resistance, thus allowing ground currents of approximately 1400 amperes to flow. The circuits selected to apply the grounds were such as to give the longest possible paths for induction between the fault bus and the 12-kv. buses. In this test as in the previous tests, meters were inserted in all fault circuits including the one under test. In no instance was there faulty relay action or indication of stray currents due to this disturbance to the switch house.

Relay Settings

(a) Instantaneous overload relays operated from the 200/5-ampere fault ground bus current transformers are set for 2½ amperes to operate on a fault current of 100 amperes. This setting was determined from the amount of stray current that was found to flow during ground tests in circuits other than the one under test and gives a factor of safety against incorrect relay operation. It was thought desirable to operate on the lowest possible value of fault current that would insure correct operation.

(b) Time delay relays were set for one second for back-up protection on bus tie oil circuit breakers. Previous tests had shown that the large bus tie breakers required 21 cycles to clear the arcing contacts so that the complete opening operation would be completed in 4/10 second and with the time delay relays set for one second, there is ample time for a fault to clear before the operation of the back-up breakers.

The Fault Ground Bus in Service

Between the time of the last series of tests and the time that the fault ground protection system was put into service, observations were made daily of any operation of fault ground relays on system or station disturbances. Before locating the causes for the circulating current which existed in several of the fault circuits prior to the tests, there had been operations of the fault ground relays due to system disturbances which would have virtually isolated the station had the breakers controlled by these fault ground relays been tripped. No indication of such conditions existed during this period of observation which extended for several weeks and so the system was put into operation on May 3, 1929. These same observations are being continued and certain recent severe system disturbances prove that no incorrect operation need be anticipated from this cause. It is proposed to make periodic tests on certain of the fault circuits similar to those described and also to make further resistance measurements between fault circuits to see if the aging of the building will increase this resistance and make correct operation even more certain. A few resistance measurements taken three months after the initial check showed the resistance to ground on one fault circuit to have increased 30 per cent.

During routine station and system operation one operation of the fault ground system has occurred and this was due to accidental contact with a 12-kv. circuit rather than a breakdown of equipment. A workman cleaning insulators on dead equipment came in contact with an energized contact of a disconnect switch causing an arc which carried to the fault ground bus circuit in the compartment. The 12-kv. section was isolated immediately through action of the fault ground relays. An idea of the speed in which the entire operation took place can be gained from the fact that the man escaped with comparatively minor burns.

Conclusions

It is expected that the foregoing application of the fault ground bus system of protection to an isolated-phase switch house will give service of an unusual degree of reliability.

For any possible failures of switchgear, feeder reactors, or bus reactors, the disturbance in the switch

house itself should be limited to a relatively small amount of apparatus.

For each protected section a low resistance path of high current capacity is provided and single-phase or other fault currents are definitely directed so as to immediately clear the switch house of the cause.

The insulation and isolation of the separate building compartments renders more effective the protection by the fault ground bus.

Back-up circuit breaker protection actuated by relays with a small time delay serves to prevent the spread of the disturbance outside of the phase room in which it originates in the event of a continued arc.

While it is not claimed that the fault ground bus is anticipatory in its functions, it is expected that failure of the insulation of a bus section or flashover of switchgear will cause that section to be cleared promptly, so that the loss of synchronous apparatus on the system will be avoided.

With the concentration of generating capacity in such switching centers as that of Brunot Island, where short circuits of unusual magnitude are to be considered, the fault ground bus system offers a protective scheme which acts to relieve in a measure the duty of oil circuit breakers, to safeguard service, and reduce life hazards.

With reference to costs, it may be stated that the isolated-phase vertical arrangement described, resulted in a cost of switch house, switchgear, and accessories, including oil circuit breaker and instrument control, fault ground bus, heating, ventilating, lighting, etc., considerably lower than corresponding designs of grouped phase arrangement on which studies and estimates were made.

The type of building construction adopted resulted in a cost slightly in excess of a design estimated on, which was based on ordinary standards for building construction omitting insulating joints and segregation of phase rooms.

The fault ground bus and the associated details of electrical and mechanical construction involved in the isolation and segregation of phase rooms and groups of switchgear, buses, etc., amounted to a relatively small percentage of the total cost. Apparently phase isolation of this type compared with grouped phase design is, inherently, less expensive, and it is believed that there is afforded by this design a superiority of operation, greater safety, and the minimizing of faults in an indoor switching station.

Appendix

A list of the main equipment controlled from the switch house follows:

Generators

5 generators, each 14,400 kw.
1 generator, 35,000 kw.
1 generator, 60,000 kw., on order, 1930 installation.
1 station auxiliary generator, 2300-volt, 3000-kw.

Transformers

2 40,000 kv-a. banks 11/66 kv.
2 15,000 kv-a. banks 11/22 kv.
1 10,000 kv-a., star delta grounding bank with a 15-ohm grounding resistor for the 11-kv. system.
Station auxiliary banks, 2300- and 440-volt.

Feeders (11 kv.)

27 feeder positions, 17 of these positions being bifurcated, making a total of 44 feeders.

Reactors

Synchronizing Reactors with Resistors

2 sets of three single-phase units, each of 4/10 ohm resistance and of 2000-ampere capacity.

Feeder Reactors

For each feeder position a set of three single-phase units, each of ½-ohm resistance and of 600 amperes capacity.
One set of these is used in the supply to the 11-kv. grounding bank.

Discussion

A. W. Rauth: It is readily seen that the purpose of this construction is not to eliminate faults but to isolate the fault in the shortest possible time after it occurs. The more common station design is such that the relays on the station feeder breakers must be given a time setting so as to make them selective with substation breaker relays. The station relay time setting often becomes rather long and if any bus-protection scheme other than differential protection is used the bus protection relays must be given a still longer time setting so as to be selective with the station feeder breakers. The insulated fault ground bus provides an excellent means of using sensitive, instantaneous relays that operate only in case of station faults. If a fault occurs outside the station the fault current path is not through the station protective relays since the entire building is insulated from ground except for the fault ground bus. This is a much better method for bus protection than the differential method. The differential method in addition to requiring a large number of current transformers, has the disadvantage that it is difficult to balance satisfactorily a large number of current transformers (on account of their dissimilar characteristics) so that sensitive relays can be used that will not operate on through faults.

The use of the fault ground bus reduces the required interrupting capacity of breakers only if it is assumed two line-to-line or three-phase faults will not occur. This is a reasonable assumption because a line-to-ground fault should occur before any other fault occurs in this type of installation. Provision is made, however, for two simultaneous ground faults and therefore the breakers cannot be as small as one might conclude by considering only the maximum ground current.

Reference to the causes of low resistance and zero resistance between phase and ground indicates that there are possibilities of the various insulated building sections becoming electrically connected. Such connections could readily cause faulty relay operations, also considerable care must be taken when changes or additions are made so that the various insulated sections do not become electrically connected. The current transformer leads are insulated from the switchboard by one-to-one insulating transformers which may cause inaccurate metering.

Since the amount of fault ground current is limited by the connected synchronous capacity, the reactance of the various circuits, the reactance of the grounding transformer and the neutral resistor, why was it considered necessary to use a neutral resistor instead of providing a smaller grounding transformer which would accomplish the same purpose?

S. M. Hamill: The same difficulties, which Messrs. Stanley and Hornibrook mentioned in their paper, of freeing the fault bus from foreign grounds were experienced at the Columbia Station of the Columbia Power Company. After the foreign grounds were removed, a permanent test set was installed for the purpose of measuring the resistance of the fault bus to ground, so that any foreign grounds occurring in the future could be detected and removed before they might cause incorrect relay operations.

A disconnecting switch was installed in the fault bus just ahead of the connection with the station grounding system. This switch was paralleled with a safety gap having a breakdown voltage of 250 volts, so that should a flashover occur when a measurement was being taken no injury to the operator would result. The resistance measurement is made with 120 volts d-c. supplied through a voltmeter from the small motor-generator set. A toggle switch is arranged on the switchboard so that either section of the fault bus may be measured. These measurements are made three times a day.

With this apparatus it is not necessary to obtain a main bus outage to determine that the fault bus is in satisfactory operating condition.

I should appreciate it very much if Messrs. Stanley and Hornibrook would clear up a point in their paper which I have missed. It seems to me that, since pains were taken to insulate the apparatus connected to the fault bus from ground, very little additional benefit to fault bus operation could be derived from insulating the building sections. Also, it seems that this would not materially decrease the possibility of a phase-to-phase short circuit, since a simultaneous flashover of two different phases would have to go to the fault bus which is a solid metallic circuit for all phases.

H. R. Summerhayes: This matter of protection against trouble on buses has been studied by some of the best brains in the electrical industry for the last twenty or thirty years. Only two well established systems of bus protection have resulted. One is this fault ground bus, and the other is the differential protection.

The differential protection, on account of the number of current transformers and the difficulty of balancing them, is well adapted only to stations in which a small number of large circuits go from each bus section, like a station in which you step up to a high voltage, that is, one having a few large transformers and one or two generators connected to each bus section. In such a case the differential protection is relatively simple and is effective.

In a station like Brunot Island, where you have a large number of feeder circuits connected to each bus section, the differential protection is not only expensive but complicated, and, on account of the great amount of equipment involved, may not be so reliable. The ground fault bus seems to be the best scheme. In using the ground fault bus, however, very close attention must be paid to detail, as was done by the designers of this station. Every part of the building must be insulated from the other parts.

There are other ways to accomplish the same thing. For instance, in each room, each bus section could consist of a number of steel cells, or the switches could be mounted on steel framework, and all of that steel framework supported on porcelain insulators and grounded only through a fault bus. That could be done inside of the building, or, as has been done in the State Line Generating Station, such a steel equipment could be erected outside of the buildings, and the posts supporting each bus section insulated from the ground and connected to the ground only through current transformers. The State Line equipment offers an ideally easy way to arrange a fault bus.

In arranging a fault bus and going through the difficulties of insulating the building and all the close attention to detail, some expense is involved. In this case, apparently, this expense was justified, since it seems that one life has been saved by the quickness of the equipment in snuffing out the fault. A considerable amount of expense is justified, aside from any question of safety to employees, by the fact that a bus trouble may be very serious, involving the shutting down of the whole station if the buses are not sectionalized.

G. B. Dodds: From an operating standpoint I should like to say that from the tests made on this installation, we are thoroughly satisfied that this protection will function satisfactorily for faults inside of the station and that it will not operate for faults outside of the station.

There are several reasons why we feel it is preferable to the standard differential protection, among which are the increased sensitivity for small fault currents without increasing the danger of operating on outside faults; and the decreased probability of defective wiring causing false operation for through faults. We had an example of this latter trouble when during a line fault we dropped one complete bus section at one of our large stations due to a ground on a current transformer lead. We also believe that fault ground bus protection will be maintained more easily than standard differential protection, and we feel that the insulation between different sections will improve rather than deteriorate as time goes on and the concrete dies out.

In regard to the question asked concerning the reason for using resistance in the neutral of our grounding bank rather than getting the necessary impedance by increasing the impedance of the grounding bank itself: one factor was the effect of the phase angle of the fault current on the direction ground relays which we had installed on our system. These relays obtain potential from inside the delta of a set of star-delta-connected auxiliary potential transformers, and have the greatest closing torque when the current in the current coil of the relay and the potential on the potential coil of the relay are in phase.

We have found from tests that with reactance only in the neutral, relays of this type would reverse their polarity under some conditions of fault, and also in case their polarity did not reverse, a very small amount of closing torque would be obtained due to the phase angle between the current and potential.

As we did not wish to discard all of the ground relays on our system, we retained the resistor in the neutral of the grounding bank. However, there is now available a means of changing our relays over so that they will work properly on a system grounded through a reactor, and we are considering the use of a reactor in the neutral of a new grounding bank which is to be installed.

D. D. Higgins: In the Chicago stations with the fault ground bus over the last two years we have had something like six or seven faults, and all of them have been cleared very promptly, and a minimum of damage has occurred. In one or two cases it was rather difficult to find where the fault had developed. We consider that the fault ground bus is one of the outstanding advancements in switch-house design. But I do want to point out that as long as we are grounding buses for the protection of workmen, we are not entirely free from the hazards of three-phase bus short circuits which are beyond the scope of fault bus protection. That is one thing that the designers must keep in mind.

F. C. Hornibrook: Mr. Hamill asked a question concerning the need for insulating the various sections of the building one from the other, since pains had been taken to insulate the equipment to which the fault ground bus was attached.

This question is misleading and shows that we have not made entirely clear just what equipment is insulated from the building construction. On the twelve uninsulated fault ground circuits connection is made to equipment which is anchored solidly into the building construction so that the reinforcing steel in the walls and ceilings as well as the bases of the equipment are maintained at ground potential. The only case in which equipment is insulated from the building construction is when such equipment is connected to a fault circuit that has crossed an insulated building split which is the case with bus tie oil circuit breakers and certain disconnect switches. Equipment associated with the synchronizing bus tie circuits is also insulated from the building construction since the fault ground bus protection of these circuits overlaps that of the main bus protection and must be kept separate and selective.

Increased Voltages for Synchronous Machines

BY C. M. LAFFOON[1]

Associate, A. I. E. E.

Synopsis.—The appreciable increase in the rating of generators, generating stations, and interconnected systems has resulted in large currents to be handled by generators, circuit breakers, reactors, cables, and station bus structures. This paper covers a discussion of the limitations on large generators and generating equipment by the present standard voltages of generation, the necessity for increasing the values of generated voltage, and the design, manufacturing, and operating problems involved in building high-voltage turbine generators.

* * * * *

At the present time serious consideration is being given to increasing materially the generated voltages of steam-turbine generators. Generators of higher output are being required to meet the needs of growing loads. The increased currents which must be handled have imposed heavy duties on equipment such as circuit breakers, switches, cables, reactors, and other auxiliary apparatus. On account of the limitations of such equipment and the growing cost and complication of handling heavy currents, it is thought desirable to increase the generator voltage which will allow a corresponding decrease in current.

Approximately 90 per cent of the power companies in this country generate at either 13,200 or 13,800 volts and most of the remainder at 11,000, 12,000, and 12,800 volts. During the last three years several large generators have been built with 22,000-volt windings and even higher voltages are being considered.

It is the purpose of this paper to discuss the effect of increased generated voltage on the manufacture, cost, performance, dimensions, and reliability of large turbo generators. The paper is not intended to cover other phases of the matter such as reduced central station cost or decreased losses. These things must be determined for each particular station or power system on the basis of cost, performance, reliability, and life of the combined generating and distributing equipment.

It should be pointed out that in the majority of cases in this country higher voltages are not needed for the sake of facilitating the transmission and distribution of electrical energy. In most cases it would still be necessary to use step-up transformers. Most of the generating stations are located considerable distances away from the distribution centers and consequently rather high transmission voltages are required which would necessitate using step-up transformers even though the generated voltages were doubled.

Two other points should be mentioned. The first is that from the standpoint of the generator alone it is possible to build very large machines at the present voltages. It is feasible to build 4-pole, 60-cycle, 1800 rev. per min., single-unit generators with present standard 11,000 to 13,800 voltage windings for ratings up to 125,000 kv-a. at 80 per cent power factor. The data in Table I are arranged to show the currents, number of conductors, number of slots, number of parallel circuits, and the winding arrangement for turbine generators of representative ratings from 62,500 kv-a. to 187,500 kv-a. for various voltages.

TABLE I

STATOR CURRENT, CONDUCTOR, AND SLOT REQUIREMENTS FOR 4-POLE, 1800-REV. PER MIN. TURBINE GENERATORS AT DIFFERENT VOLTAGES

Kv-a.	Volts 11,000	Volts 12,000	Volts 13,800	Volts 16,500	Volts 22,000	Volts 33,000
62,500 Kv-a.						
Amperes	3280	3000	2610	2185	1640	1092
Conductors	80.75	88.4	101.4	121.	161.5	242.
Slots	84.0	60	72	60	72	60
Connection	YY	YYYY	YYYY	Y	Y	Y
Conductors per slot	2	6	6	2	2	4
Amperes per slot	3280	4500	3920	4370	3280	4368
75,000 Kv-a.						
Amperes	3935	3605	3140	2625	1970	1312
Conductors	67.4	73.5	84.4	101	134.5	202
Slots	72.0	72.0	84.0	54.0	66.0	54.0
Connection	YY	YY	YY	Y	Y	Y
Conductors per slot	2	2	2	2	2	4
Amperes per slot	3935	3605	3140	5250	3940	5248
93,750 Kv-a.						
Amperes	4915	4500	3920	3280	2460	1640
Conductors	54	58	67.7	80.75	107.8	161.5
Slots	54	60	72	84	54	54
Connection	YY	YY	YY	YY	Y	YY
Conductors per slot	2	2	2	2	2	6
Amperes per slot	4915	4500	3920	3280	4920	4920
125,000 Kv-a.						
Amperes	6560	6010	5230	4375	3280	2190
Conductors	40.3	44	50.7	60.5	80.75	121
Slots	72	84	54	60	78	60
Connection	ΔΔ	ΔΔ	YY	YY	YY	Y
Conductors per slot	2	2	2	2	2	2
Amperes per slot	3800	3470	5230	4375	3280	4380
187,500 Kv-a.						
Amperes	9835	9020	7835	6555	4920	3280
Conductors	27	29.4	33.8	40.5	53.8	80.8
Slots	....	....	....	....	54.	60.
Connection	....	....	....	....	YY	YYYY
Conductors per slot	....	....	....	....	2	6
Amperes per slot	....	....	....	....	4920	4920

These data are based on machines designed for 80 per cent power factor conditions and operate at approximately unity short circuit ratio. It is apparent from the data in this table that from the standpoint of required number of conductors and stator slots, the most satisfactory voltage range for large turbine generators is from 13,800 to 22,000 volts.

The other point is that the limit in circuit-breaker

1. Power Engineering Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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duty can also be met by providing the generator with two or more independent windings and by separating the generating station and system into units which are tied together only at points on either a high-tension or a low-tension network.

These alternatives should of course be considered though they cannot be fully discussed here.

Problems Involved in the Manufacture of High-Voltage Generator Windings

Type of Insulation. The most important problem involved in the design and construction of high-voltage rotating machines is the insulation of the stator windings. A satisfactory insulation material for use on the strands, conductors, and coils of high-voltage windings should conform to the following specification requirements:

1. High breakdown strength when subjected to voltage.
2. Low dielectric losses at normal operating voltages and at test voltages.
3. High resistance to corona and static discharges.
4. Non-hygroscopic.
5. Relatively high thermal conductivity so that the stator copper losses can be dissipated with a minimum temperature drop through the insulation.
6. Sufficient mechanical strength and flexibility for applying it to the strands, conductors, and coils in a satisfactory manner.
7. Resistance to vibration and movement.

Mica is the only material available at the present time which approaches all of these desired characteristics. Its most serious limitation is that it is available only in small sheets or flakes, and does not have high mechanical strength. In order to put mica in such shape that it can be applied to conductors as insulation, it is necessary to apply it to a paper or cloth base to give sufficient mechanical strength. The desired degree of flexibility is obtained by using relatively thin flakes and building up layers of overlapping flakes, together with a satisfactory bonding material. The characteristics of the bonding material should correspond to the desirable characteristics of the insulating material. It is especially essential that the amount of bond and its vapor pressure be low, so that gases will not be liberated when subjected to heat and cause looseness in the insulation layers, and swelling or bulging of the insulation at the unsupported sections. The built-up insulation can be made in the form of tape or wide sheets, and applied to the coils in these forms.

Treated cloth is also a satisfactory insulating material. It is stronger mechanically and more flexible than mica tape, and when properly impregnated has a higher voltage breakdown strength. Its most serious limitation is that it is susceptible to injury from corona, static discharges, and high temperatures. Its application is confined to parts of the coils, connectors, and leads which are of unfavorable shape, and difficult to insulate with mica tape, and which operate at relatively low temperatures and are free from corona and static discharges.

After doing a large amount of development work and making tests on insulated coils, it is felt that the insulation materials which are used on present lower voltage windings, are satisfactory for higher voltage windings. It is necessary to give more care and supervision to the manufacturing operations in building the insulation, applying it to the coils, handling the coils through the respective manufacturing processes, assembling the coils in the machine, making insulation tests, and conditioning the machine prior to going into service.

Application of Insulation to High-Voltage Stator Coils. In building coils for high-voltage generator windings, the individual strands and conductors of multiple turn coils are insulated throughout the entire length with mica tape. The company with which the writer is affiliated uses micarta folium wrappers for the straight part of the coil sides. The end turns, connectors, and leads are insulated with mica tape, treated cloth tape, or a combination of both kinds of tape. The micarta folium insulation used on the straight portion of the coil has been improved during the past few years by the introduction of a bonding material which has a lower dielectric loss, higher breakdown strength, and greater flexibility than the older type bond. The increased flexibility of the wrapper makes it feasible to use a greater percentage of mica in the micarta folium. The micarta folium wrapper is in one piece with respect to the length of the coil side, and is wrapped on and baked simultaneously by means of an electrically heated automatic wrapping machine. All coils are "steam" pressed on the straight parts after insulating in order to remove the volatile matter and obtain a more compact insulation free from air spaces. The treated tape on the end turns, connectors, etc., is applied by hand. Special attention is given to the design and actual manufacturing operations in making the joint between the two kinds of insulation, so that it will satisfactorily withstand the voltage stresses which exist under actual operating conditions.

Tests on Insulation for High-Voltage Windings. The use of treated cloth tape on the end turns for the coil insulation is desirable on account of the fact that with its greater mechanical strength than mica tape, it can be applied more tightly, and a more compact insulation obtained. Numerous tests have been conducted to determine whether the end insulation and the joint between the mica folium and the end insulation were satisfactory for high-voltage windings. Coils were insulated on the ends with treated cloth tape and with several grades of mica tape. The mica tape was vacuum treated before being applied to the coils. All tests were made at usual room temperatures. The average value of breakdown voltage for the coils insulated with mica tape for 13,200-volt normal operation was approximately 75 kv. and for the coils with an equal thickness of treated cloth insulation, the breakdown voltage was

100 kv. Mica tape for 22,000-volt operation failed at an average value of approximately 100 kv., whereas coils insulated with an equal thickness of treated cloth withstood approximately 140 kv. The voltage was applied momentarily in all cases. All of the test results indicated that treated cloth tape is more satisfactory for insulating the end windings than mica tape and that 25 to 50 per cent greater test voltage can be withstood. The test results indicate that mica tape is also a satisfactory insulation for the end turns and other related parts.

A test bar approximately 8 ft. long was made to represent a section of a stator coil for a large capacity 22,000-volt turbine generator. The bar was insulated with micarta folium suitable for 22,000-volt service, and the ends were covered with micarta tubes in order to obtain sufficient creepage for testing at high voltages. The joints between the micarta folium insulation on the bar and the micarta tubes were sealed with treated cloth tape. The bar was tested at 65 kv. for one minute and did not fail. The test voltage was then raised to 100 kv. and held for 30 seconds and no failure occurred. In making the test, the tin-foil grounding sheath was extended out over the joint, whereas in an actual generator, a long creepage distance is provided from the joint to ground. Built-up sections with 22,000-volt micarta folium insulation have been tested at 175 to 200 kv. momentarily without failure.

Steps have been taken to eliminate corona and static discharge around the end windings during testing and under normal operating conditions. In the slot portion, the coil is covered with asbestos tape, and a relatively high resistance conducting material is applied to this portion of the coil. No slot cell is used and the entire embedded surface of the coil is at ground potential; consequently, no static discharge can take place from the coil surface ground. The ends of the coils are covered with a layer of asbestos tape which acts as a high-resistance conductor and decreases the amount of discharge at the end of the slot and around the end windings.

With higher voltage windings, it is felt necessary to keep metallic structural parts remote from the end windings in order to decrease corona and reduce the voltage stress on the end portions of the winding. The coil ends are roped down to micarta coil supports which are distributed around the end winding periphery at frequent intervals. Fig. 1 shows the coil ends and method of bracing, which is to be used on large 22,000-volt, 1800-rev. per min. turbine generators. In the case of higher voltage stator windings, the mechanical stresses on the end turns are reduced due to the fact that the currents are smaller. Hence, the coil end bracing is a less difficult mechanical problem than for the case of lower voltage machines of the same rating.

Insulation Tests. It is necessary, in the construction of higher voltage generators, to increase the magnitude of the voltage for the insulation tests at the different stages of the manufacturing operations, and the difficulties involved in making the insulation tests increase very rapidly as the test voltages are increased. In view of the fact that the dielectric losses increase very fast for high voltages, it is felt advisable to consider the necessity for maintaining the test voltages for appreciable lengths of time. With the prolonged high-voltage test, the insulation heating due to dielectric losses and surface creepage may become so great that injury to the insulation will result, and the test actually produce more harm than good. It is believed that the present standardized final test voltages of twice normal plus 1000 for one minute can be satisfactorily met for 22,000-volt machines. However, for final test voltages in excess of 50 kv., the length of test should be materially reduced. A shorter time of voltage application

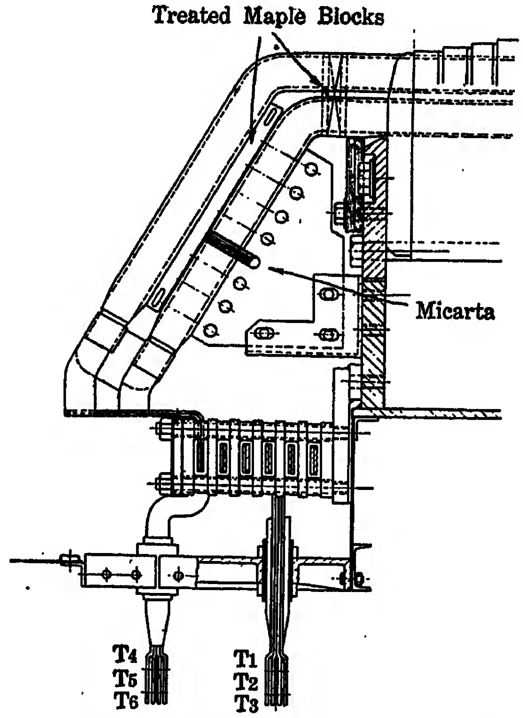

Fig. 1—Showing Method of Bracing Coil Ends on 22,000-Volt Generator

should be satisfactory to locate any defects in the insulation, and would be considerably less liable to injure the insulation by excessive heating. If desired, two or more tests of shorter duration could be made with sufficient time interval between tests to permit the insulation to cool.

Shape of Conductors and Voltage Gradient. In designing the conductors of high-voltage windings, special consideration must be given to the shape of the conductors in order to limit the potential stresses at different sections of the insulation. It is not only necessary that the average voltage per unit thickness of insulating material be kept within the safe working range, but stress concentration due to sharp corners and edges must be avoided. The circular conductor is the ideal shape from the standpoint of minimum stress concentration. Fig. 2 shows the electrostatic field for a

circular conductor with insulation thickness required for a 22,000-volt winding. For a given total voltage to ground, the series concentric cylindrical conductor arrangement is the ideal arrangement from the standpoint of minimum potential gradients, as shown by Figs. 3 and 4. This type of conductor was used in the construction of a 33,000-volt turbine generator by the

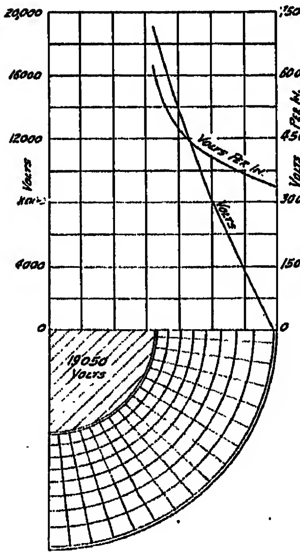

Fig. 2

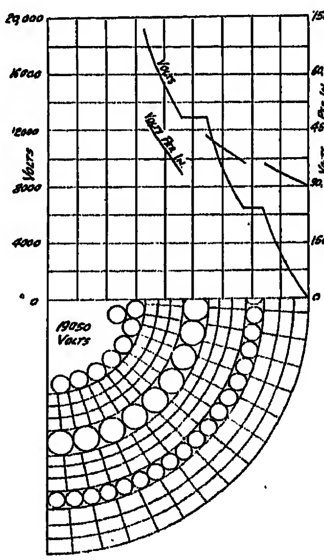

Fig. 3

Fig. 2—Curves showing Gradient and Voltage Drop Across Insulation for a Single-Core Conductor

Fig. 3—Curves showing Gradient and Voltage Drop Across Insulation with Concentric Conductors

Parsons Manufacturing Company. Figs. 2, 3, and 4 have been reproduced from a paper by Messrs. Parsons and Rosen describing this generator which will be discussed more fully in subsequent paragraphs.

With the American type of construction in which it

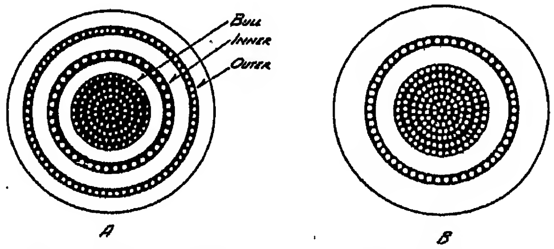

Fig. 4—Sections through Conductor Bars

is considered necessary and essential that the coils be placed in open slots, it naturally follows that the conductors are rectangular in shape. If standard rectangular copper sections were used for the strands, the built-up conductor and coil would have relatively sharp corners, and there would be stress concentration at these points. The electric field for a conductor with square corners is shown in Fig. 5. In this particular case, the field would be as shown in Fig. 6, if the corners of the coils were provided with a radius equal to one-quarter of the copper width. Since the present practise is to transpose strands of the conductor in the buried part of the coil, it becomes a difficult and expensive proposition to put the necessary radii on the respective strands by hand. In this connection, it is felt that a half-round strip or strip with well-rounded corners, should be placed at the top and bottom edges of the top and bottom coils respectively. This strip would be insulated from all of the strands except possibly one and provided with the usual amount of strand insulation. This strand would assume the potential of the

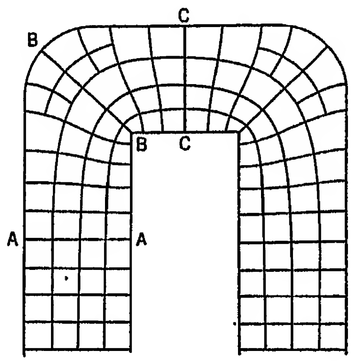

Fig. 5a—Electrostatic Field

Rectangular conductor with square corners. (33,000-volt insulation)

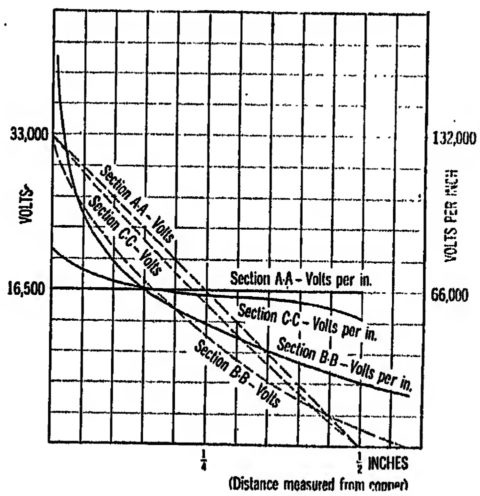

Fig. 5b—Volts and Volts per Inch

Rectangular conductor with square corners. (33,000-volt insulation)

conductor to which it is applied, and would aid materially in reducing the stress concentration at the corners as shown in Fig. 7. In all of these cases, the outside surface of the coil is provided with an asbestos tape covering which is filled with a high-resistance grounding compound. The electrostatic fields are based on the outside surface of the coil being at ground potential. As a further means of reducing the concentration of stress on different parts of the insulation, it is proposed that equipotential surfaces be provided at different intervals in the insulation. The wrappers can be applied in approximately three parts, and conducting

films can be located at the corners of the coil over restricted sections, and thus establishes definite potential surfaces. The type of conducting material and its arrangement can be controlled so that no resistance losses of appreciable magnitude are introduced due to circulating currents. The magnitude and distribution of the electrostatic field are shown in Fig. 8.

Temperature Gradient through Insulation. It is necessary in the construction of higher voltage windings to use an increased thickness of insulation on the stator coils. There will be a corresponding increase in the temperature drop through the insulation in dissipating the stator copper loss. After the unit is placed in operation, the insulation is subjected to difficult service conditions on account of the relative movement between the insulation and the copper due to appreciable temperature differences. Whether this increased duty on the insulation will appreciably reduce the life of the winding below that now obtained on lower voltage machines can only be determined after several years of operation.

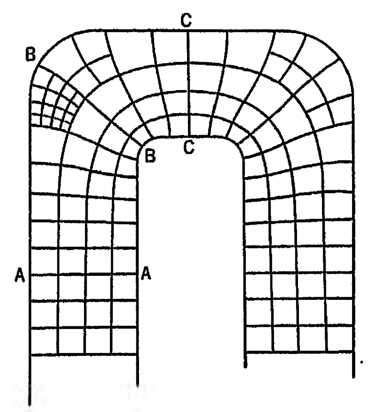

FIG. 6A—ELECTROSTATIC FIELD

Rectangular conductor with round corners. (33,000-volt insulation)

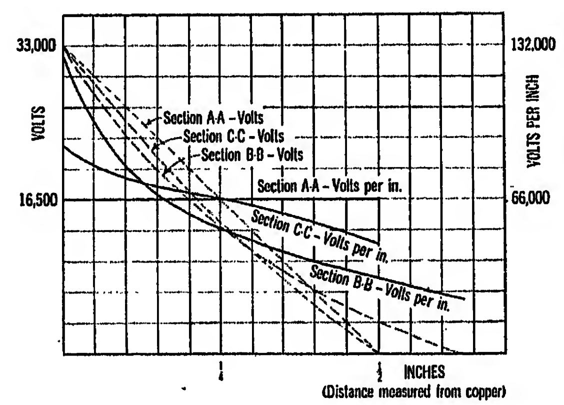

FIG. 6B—VOLTS AND VOLTS PER INCH

Rectangular conductors with round corners. (33,000-volt insulation)

EFFECT OF INCREASED VOLTAGES ON GENERATOR COST, WEIGHT, AND PERFORMANCE

In extending the design of any apparatus into unknown regions, there is a forced necessity for basing engineering judgment and conclusions on past experiences, and present available information. There are insufficient data available at the present time to determine the best thickness of the insulation for the higher voltage generator windings. With a given type of insulation, the optimum thickness of insulation must be based on a compromise between the average volts per inch of insulation and the total thermal drop through the insulation due to the stator winding copper loss. Based on experience with micarta folium insulation on 13,200-volt machines, it is believed that the insulation thickness should be increased approximately 45 and 110 per cent respectively for 22,000- and 33,000-volt windings. The data in Table II have been arranged to show the total space required for micarta folium

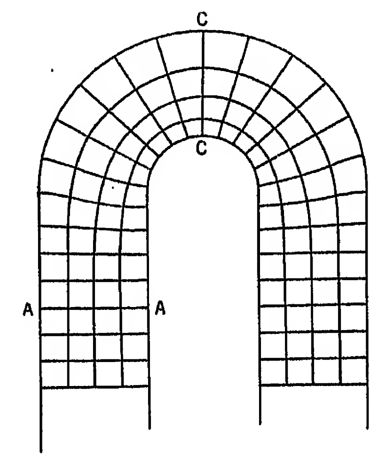

FIG. 7A—ELECTROSTATIC FIELD

Rectangular conductor with half round strip on top. (33,000-volt insulation)

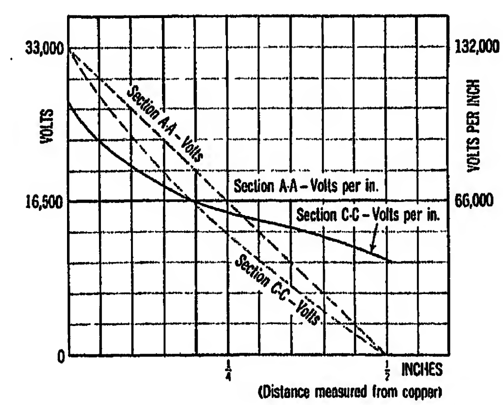

FIG. 7B—VOLTS AND VOLTS PER INCH

Rectangular conductor with half-round strip on top. (33,000-volt insulation)

insulation for different voltages and slot combinations on 4-pole, 1800-rev. per min., 60-cycle turbine generators.

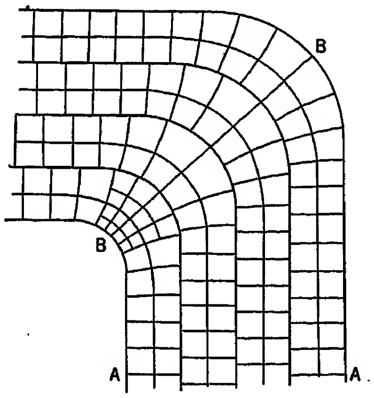

Fig. 8a—Electrostatic Field

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor. (33,000-volt insulation)

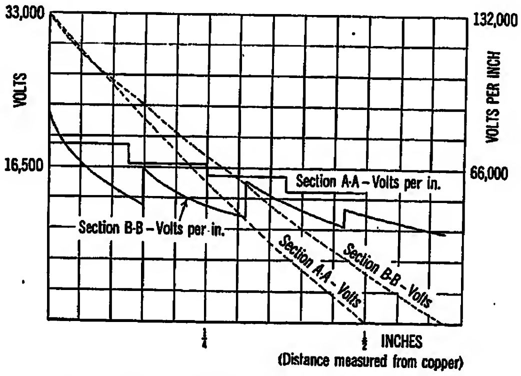

Fig. 8b—Volts and Volts per Inch

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor, all of equal length. (33,000-volt insulation)

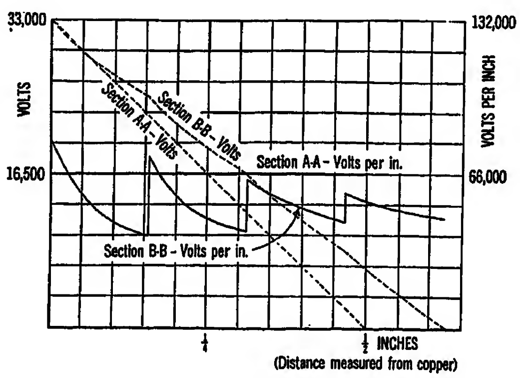

Fig. 8c—Volts and Volts per Inch

Rectangular conductor with round corners. Three conducting films equally spaced in insulation, completely surrounding conductor; length adjusted to give equal areas under films. (33,000-volt insulation)

On the basis of the data in this table, 40 per cent greater total insulation space is required for a stator with 84 slots than for 60 slots for any given voltage, and for any given slot combination, 110 per cent more insulation space is required for the 33,000-volt winding than for the 13,200-volt winding. If the 33,000-volt winding necessitated the use of 84 slots, an increase in the total insulation space of approximately 200 per

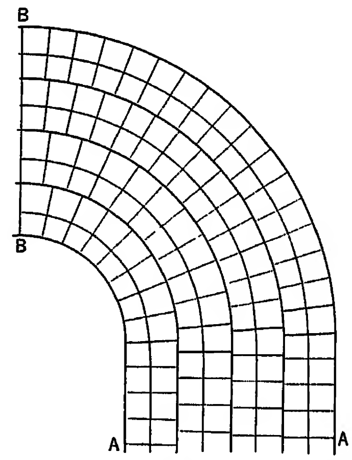

Fig. 9a—Electrostatic Field

Rectangular conductor with half round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor. (33,000-volt insulation)

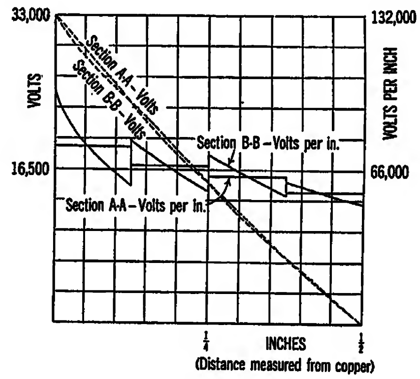

Fig. 9b—Volts and Volts per Inch

Rectangular conductor with half-round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor, all of equal length. (33,000-volt insulation)

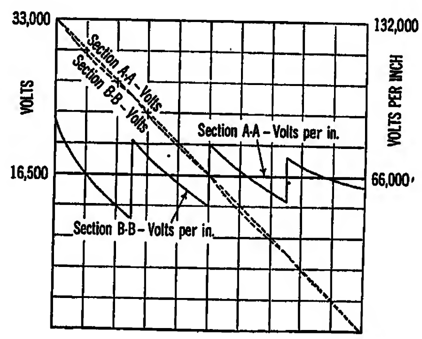

Fig. 9c—Volts and Volts per Inch

Rectangular conductor with half-round strip on top. Three conducting films equally spaced in insulation, completely surrounding conductor; length adjusted to give equal areas under films. (33,000-volt insulation)

cent would be required over that for a 13,800-volt winding with a 60-slot stator core. In the case of the lower voltage windings, the handicap of increased

insulation space for the larger number of slots and consequent reduction in available space for the copper is more than offset by the increase in the external surface of the copper for dissipating the copper losses. However, in the case of higher voltage machines, the total insulation space required is so great that no space is available for the copper with the larger number of slots, and it is necessary to use a relatively small number of slots.

With the increased thickness of insulation on the coils for high-voltage windings, it is necessary to work the stator copper at a lower current density on account of the higher thermal drop through the insulation. This means that a greater percentage of the stator periphery is required for the stator copper than for lower voltage machines. With the greater space required for insulation and stator copper, it is necessary to increase the length of the stator core in order to keep the magnetizing flux density in the teeth within a range of safe working values. If the rating and voltage are such that a larger number of stator slots is required, the length of the machine will have to be increased further, on account of the additional insulation requirements. Preliminary studies and estimated costs indicate that the manufacturing cost of a 22,000-volt turbine generator of relatively large capacity would be approximately 20 to 25 per cent more than that of a generator of the same rating wound for a suitable lower voltage. Similarly, the increase in cost for a 33,000-volt generator would be on the order of 40 to 50 per cent. There would be a corresponding increase in the weight and dimensions of generators when built for high-voltage service.

TABLE II
INSULATION SPACE REQUIRED FOR 4-POLE, 1800-REV. PER MIN., 60-CYCLE TURBINE GENERATORS WOUND FOR DIFFERENT VOLTAGES

No. of slots	Per cent of stator periphery required for different voltages				
	11,000	13,200	16,500	22,000	33,000
54	12.0	13.9	16.3	20.2	30.2
60	13.2	15.4	18.1	22.4	33.6
66	14.6	17.0	19.9	24.7	37.0
72	16.0	18.5	21.7	26.9	40.3
78	17.3	20.1	23.5	29.1	43.7
84	18.7	21.6	25.3	31.4	47.0

The efficiency of such units would be reduced due to the greater bearing and windage friction losses on account of the increased rotor weight and dimensions and increased load and excitation losses. With the relatively small number of wide slots which are required the ratio of slot opening to air gap will be materially increased, and this will result in an increase in the rotor pole face losses. It is expected that the efficiency of the high-voltage machines will be from 0.25 to 0.5 per cent less than for a suitable lower-voltage machine. Whether such units can be justified from the cost and performance standpoints depends on the savings that can be made in the cost and performance of circuit breakers, cables, and other related auxiliary equipment.

History of High-Voltage Synchronous Machines in the United States

The earliest high-voltage synchronous machine built by the Westinghouse Company was a 6000-kw., 16,500-volt, 50-cycle, 750-rev. per min. turbine generator for the Edison Electric Company of Los Angeles in 1906. A 15,000-kv-a., 18,000-volt, 50-60-cycle frequency changer set was built for the Southern California Edison Company in 1919. Synchronous condensers of 5000-, 10,000-, and 15,000-kv-a. rating at 18,000 volts were built for the same company in 1921 and 1923. These machines have experienced no cases of stator winding trouble since installation.

The 11,000-volt, single-phase turbine generators for the Norfolk and Western, New York, New Haven, and Hartford, and Virginian Railways Companies are provided with 19,000-volt insulation on the stator windings and are operated with one terminal grounded. The electric potential between the main insulated lead and grounded lead is 11,000 volts and is therefore 40 per cent higher than the voltage between terminal and neutral of a three-phase 13,800-volt machine when operating with grounded neutral. These machines have been in continuous service since 1915 and 1924 respectively. At the present time, a 70,600-kv-a., 22,000-volt, 1800-rev. per min. turbine generator is on order for the Northern Indiana Public Service Co. and will be placed in service during 1930.

High-Voltage Generators by the General Electric Company. The following machines of 16,500 volts and above have been built by the General Electric Company.

SYNCHRONOUS CONDENSERS (SALIENT POLE)

No. of each rating	Rating	Date of Installation
2	12,500-kv-a., 500 rev. per min., 22,000 volts, 50 cycles	1919
1	15,000 kv-a., 900 rev. per min., 24,000 volts, 60 cycles	Under construction
2	12,500 500 " " " 22,000 volts, 50 cycles	1928
	Turbine Generators	
1	100,000-kv-a., 1500 rev. per min., 16,500 volts, 50 cycles	1928
2	61,765-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles	1928-1929
2	72,941-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles	1929
1	89,411-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles	1929
1	100,000-kv-a., 1500 rev. per min., 16,500 volts, 50 cycles	Under construction
2	116,667-kv-a., 1800 rev. per min., 22,000 volts, 60 cycles	Under construction

High-Voltage Generators by the Allis-Chalmers Company. An 1800-rev. per min., 115,000-kw., 95 per cent-power factor, 18,000-volt generator is being built by the Allis-Chalmers Company for the Public Service Company of Northern Illinois. This unit is expected to be placed in service during the early part of 1931.

High-Voltage Generator by the Parsons Company. During the past year, a 25,000-kw., 33,000-volt, 3000-rev. per min., 50-cycle turbine generator was built by the Parsons Mfg. Company for the North Metropolitan

Electric Power Supply Company of England. A complete description of this machine was given by Messrs. Parsons and Rosen in the *Proceedings* of the Institution of Electrical Engineers in the early part of 1929. Since this is the first large capacity 33,000-volt generator to be placed in service, it seems advisable to call attention to some of the outstanding design features and compare them in a general way with the type of design of American-made machines.

This machine is interesting from design and construction standpoints, in that cylindrically-shaped concentric conductors, Fig. 4, are used in the stator winding, and partially closed circular-shaped stator slots are provided in the stator core. With this construction, the insulated conductor must be inserted in the circular tunnel-shaped slots at the ends of the machine and pushed through the entire core length. This requirement practically precludes the possibility of obtaining a snug fit between the conductor insulation and the perimeter of the circular slots. The inevitable looseness of the coil sides in the slots permits air spaces to exist and gives a poor heat transfer constant from the insulation to the stator iron which results in higher stator winding temperatures. It also leaves the coil free to vibrate, which may result in damage to the insulation. A further disadvantage of the bar and end connection type of winding used on this machine is the difficulty of making the electrical and insulation joints between the bar and end connectors at the ends of the stator core on account of the restricted space for working. These conditions do not exist to any appreciable extent in the case of machines of American design in which the conventional type of open rectangular-shaped slots is used. In assembling the coils in open rectangular-shaped slots, it is only necessary to push the coil radially through the depth of the slot and side packing can be readily applied, hence a snug fit can be obtained at all points.

The cylindrically-shaped coil sides of the 33,000-volt machine consist of the concentric conductors, and each conductor is provided with insulation equivalent to approximately one-third of the total insulation thickness necessary for full voltage from line to neutral. The conductors of each phase are arranged in three groups, and the three groups connected in series. The group nearest the neutral point of the winding consists of all of the outer conductors and the group nearest the lead terminals consists of the central conductors. With this winding connection system, the total insulation limits the breakdown to ground and the voltage gradient on the insulation is reduced due to the fact that definite series voltages are applied at definite points in the insulation. The cylindrically-shaped conductor lends itself readily to the application of the insulation and is free of corners which introduce high electrostatic stress concentrations. The disadvantage of this type of conductor is that for a given copper section the surface available for dissipating the copper loss is a minimum. The watts loss due to the central conductor must flow across the total or three insulation thicknesses, whereas the losses of the other two conductors flow across one and two thicknesses of insulation respectively. With rectangular-shaped conductors, the heat dissipating surface is appreciably larger per conductor, and the loss of each conductor is dissipated through the total thickness of insulation adjacent to the conductor. When comparing the relative conductor and insulation dimensions given in the paper by Messrs. Parsons and Rosen, with a three-conductor rectangular-shaped coil side on the basis of the same copper sections and same total thickness of insulation, the thermal drop in the insulation would be from 25 to 75 per cent greater for the cylindrical-shaped conductor. The actual increase in thermal drop through the insulation depends on the ratio of surface area of the rectangular and circular-shaped conductors. With the total thickness of insulation required on a 33,000-volt machine, the increase in the stator copper temperatures would therefore be approximately 7.0 to 21 deg. higher for this cylindrical concentric conductor type of coil side.

The coils farthest remote from the neutral or ground potential have only two conductors, and additional insulation is provided to give greater protection against voltage stresses due to potential surges. This feature can be handled in a similar and equally effective manner with the American type of rectangular shaped coils. At the present time, experimental investigations are under way to determine the voltage distribution between turns when the stator winding of a synchronous machine is subjected to voltage surges of different shaped wave fronts. It is hoped that this investigation will determine whether there is a need for providing additional insulation on the end turns.

The data covering the electrical characteristics of the generator show that the short-circuit ratio is only 0.6, whereas a short-circuit ratio of approximately unity is required by an increasing number of American central station companies. The efficiency of the generator, which is given as 96.5 per cent at 25,000 kw., 80 per cent power factor, is approximately 0.5 to 0.75 per cent lower than the corresponding efficiency of a 60-cycle, 1800 rev. per min. American generator of the same rating, except wound for one of the present standard voltages.

Summary and Conclusions

At the present time, there is a definite need for materially increasing the generated voltage of large steam-turbine generators due primarily to the limitations in the current-carrying capacity of the oil-filled type of circuit breakers and to the increased cost of switches, reactors, and cables for the relatively high current values at present standard voltages. Based on the results of tests and research development, and on the operating experience with several 18,000-volt synchronous condensers and 11,000-volt single-phase

turbine generators which are provided with 19,000-volt insulation and operate with one terminal grounded, it is felt that turbine generators wound for voltages between 16,500 and 25,000 volts should give satisfactory operation, provided adequate judgment and precautions are followed in their operation. It would not be recommended that a high-voltage generator be connected directly to a transmission line or distribution system unless the existing conditions were such that the windings would not be subjected to potential surges of dangerous magnitude. The cost of a 22,000-volt turbine generator will be 20 to 25 per cent more than for a similarly rated machine of suitable lower voltage. In the case of large capacity units, the increase in cost and reduction in efficiency of performance will probably be more than offset by the reduction in cost of step-up transformers, cables, and bus bars.

In the case of 33,000-volt machines, there is no operating experience available for such voltages; consequently, it will be necessary to complete a comprehensive program of research development and obtain reliable operating data on 22,000-volt generators before concluding that it is feasible to build satisfactory 33,000-volt generators. As the situation now stands, the building of a 33,000-volt machine of relatively large capacity and great importance should be undertaken jointly by the manufacturer and purchaser, as a development proposition.

ACKNOWLEDGMENTS

The writer is indebted to Mr. J. F. Calvert of the Power Engineering Department and Mr. M. G. Leonard, Summer Student, for preparing the electrostatic fields and voltage gradient curves for the insulation on the rectangular-shaped conductors.

Discussion

R. W. Wieseman: Mr. Laffoon has given us a very interesting paper on armature insulation of synchronous machinery. This paper shows very clearly that present day voltages offer no limitations to the size of synchronous machines.

In the paper, it is stated that treated cloth tape is mechanically stronger than mica tape. This is quite true when the tapes alone and the application of the tapes are considered. We are not, however, so much interested in the tape as we are in the finished insulation on the coil or bar. When mica tape or mica sheet insulation is securely cemented to a coil, it has a mechanical advantage over treated cloth insulation for large coils because mica will stand more compression and more handling than cloth insulation.

Treated cloth tape can no doubt be applied to the end portions of the coil more tightly than mica tape. On the other hand, if the mica is applied to the coil with a reasonable degree of tightness, thoroughly filled by a vacuum process, and then cushion-pressed and cemented at high temperature to the copper, a superior insulation will result.

We are in full agreement with the statement that low-voltage insulations are satisfactory for higher voltages, provided they can be thoroughly filled and protected from corona and high temperatures. This is somewhat difficult to do in air-cooled machines and so on large important machines all mica coils are recommended.

I should like to ask Mr. Laffoon why the mica tape was vacuum-treated before it was applied to the coil. This treatment may make the tape dry and stiff and it may be difficult to apply it to the coil tightly. Mica tape must be quite flexible so that it can be applied readily and it should be dried or cured after it has been applied to the coil.

The paper states that test results at room temperature indicated that cloth tape is more satisfactory for insulating the end windings than mica tape because the cloth tape stands 25 to 50 per cent more test voltage. These tests do not give a fair comparison between cloth and mica. Cloth will always stand a higher short-time voltage than mica at room temperature. Under actual operating conditions of higher temperatures and continuously applied voltage, the mica will usually stand a higher voltage and last longer than any kind of varnished fabric insulation.

Perhaps another reason why the mica did not compare so favorably with cloth is because the mica was not completely filled. To obtain the best results with mica tape insulation, all voids must be eliminated by thoroughly filling the mica with an insulating compound and the mica must be cushion pressed into a solid mass and securely cemented to the copper.

Asbestos tape is a very effective slot armor and grounding sheath for the slot portion of the coil. This tape should not be carried too far around the end portion of the coil because the surface leakage currents may overheat the end winding.

The rounding of sharp corners on high-voltage armature conductors is a step in the right direction not only because high-voltage stresses are reduced but also because the insulation itself will not be damaged so readily as when it is bent around sharp corners. Below 25,000 volts it is perhaps not so economical to employ specially shaped conductors with round corners, but in the region of 33,000 volts, conductors which give more uniform voltage stresses in the insulation can certainly be used to advantage.

In conclusion, our experience with high-voltage all-mica insulation has shown that the mica must be securely cemented to the copper and completely filled by a vacuum pressure process. It must be a homogeneous insulation (without joints) throughout the entire periphery of the coil, and it must be protected from corona and high-voltage gradients by suitable grounding sheaths.

P. L. Alger: I agree with the author in his broad conclusions, that standard insulating materials and methods can be successfully applied in machines up to 33,000 volts, and that a voltage of about 22,000 is economically desirable on the largest turbine generators.

I am not in full accord with Mr. Laffoon, however, in regard to tests on such high-voltage insulation. I consider that insulation should be designed primarily for long endurance under service conditions, and that the best measure of such endurance is the length of life of a coil under about four times normal voltage stress at a temperature of about 100 deg. cent. Many life tests of this kind have shown that coils with high momentary voltage strengths at low temperatures are often inferior to coils made of more enduring materials with lower momentary voltage strengths. For these reasons I believe any shortening of the time of high-potential tests to be unwise, and that a more reasonable procedure, if high-voltage machines are to be given special consideration, would be to reduce the voltage slightly and extend the time of test to five minutes.

The reason for requiring high momentary voltage tests has been to insure strength to resist the voltage surges which occur in practise. I consider, however, that the time is approaching when more rational means of protecting against surges than arbitrary insistence on high momentary voltage tests will be adopted. The real economic gain from high-voltage machines cannot be secured until they can be directly connected to transmission lines, and this cannot be done until surges are adequately protected against. It is well known that voltage oscillations

occur in machine windings under impressed surges, to an even greater degree than they occur in transformers. The accompanying cathode ray oscillogram (Fig. 1) taken on a 24,000-volt synchronous condenser illustrates this phenomenon. Curve *b* shows the form of a voltage wave of about three microseconds front impressed on the three lines simultaneously, and curve *a* shows the resulting voltage at the ungrounded *Y* point. The internal voltage oscillates at about 10,000 cycles frequency, and rises to about twice the impressed value. As the voltages in other parts of the winding are also high, and as the turn-to-turn voltage is high at several points in the winding, it is very desirable to use external means to prevent the application of such surges to the terminals if possible. When the *Y* point is grounded, the voltage oscillations are less severe, but in this case, triple harmonic currents flow to the lines, which may give rise to telephone interference, especially with salient-pole machines.

I believe, therefore, that we cannot yet reap the full advantage of high-voltage machines, but that we are rapidly progressing in our understanding of the difficulties in the way and that ultimately we will have means for protecting against surges, while we will tend toward the use of longer times and lower voltages in high-potential tests.

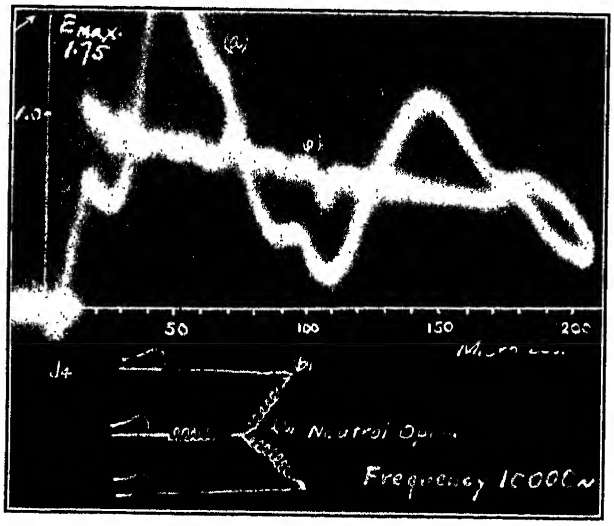

FIG. 1

There are several details in Mr. Laffoon's paper to which I wish to refer briefly. He remarks that the mechanical stresses on the end windings are lower in high-voltage machines, because of the lower currents. Since the current in each coil side of a machine of a given size and kv-a. rating is the same whatever the voltage, I do not see why the end stresses are any different either.

In the table on the seventh page the second two 12,500-kv-a., 22,000-volt condensers were built by the British Thomson Houston Company. These machines, and the very notable Parsons generator referred to by Mr. Laffoon, show that England is doing very constructive work along these lines. In Mr. Laffoon's discussion of the temperature rise of the Parsons generator, he seemed to overlook the fact that the graded insulation used results in only two-thirds the temperature rise of a normal machine of the same conductor surface area. This effect offsets the lessened area of the cylindrical conductors used and I believe the net result should be about a normal temperature rise instead of an excess of 7 to 21 deg. as Mr. Laffoon suggests.

Theodore Schou: It is very interesting to listen to the various points on insulation. Naturally, the points referred to apply to very large machines. But I do take a little exception against mica as compared with built-up insulation. My personal experience during the last twenty years has been that mica has to be treated very carefully and selected very carefully and inspected very carefully, if it is to be any good. For moderate capacity machines, I believe the so-called built-up insulation with a series of dips and tapings is the best protection. Naturally, it takes more time, but it does not necessarily take more labor to produce a good high-voltage coil with a series of dips. I do believe that such an insulation is very good for a moderate size machine, both synchronous motors and generators.

I should like to hear Mr. Laffoon's comments on the built-up insulation as to mica.

S. L. Henderson: When the subject of increased voltages for synchronous machines is considered, the question naturally arises as to the feasibility of connecting such machines directly to the line without intervening transformers. This question will arise in those sections where there is a local low-voltage distribution which is now fed by transformers connected to 13,800-volt generators. Instances can be found of distribution direct from 13,800-volt generators and there would seem to be sufficient precedent for direct distribution at these higher generated voltages. However, the conditions are not exactly parallel.

Studies made in connection with transformers have shown that the voltage surges coming from lightning discharges are of greater importance than those arising from switching. Tests with a half microsecond wave-front impressed on a generator, show that 80 per cent of the initial voltage at the terminals of the machine is impressed on the first coil and if a two-microsecond wave is impressed, 60 per cent of the voltage is impressed on the first coil. This means that several times the phase voltage may be impressed across the first coil at the time of a lightning stroke, and consequently there will be very high voltages between turns of this first coil. Subsequent to the initial surge, high voltages may occur in coils removed from the terminal, due to an internal oscillation in the machine.

The amount of lightning voltage which can reach the machine is dependent on the setting of the lightning arrester, and, therefore, the first few turns are subjected to a higher voltage surge.

The voltage generated by revolution per turn for a given size machine is essentially the same, irrespective of the terminal voltage, so that no more turn insulation is required on the high-voltage machine than on the low. However, if we also consider the lightning voltage, the turn insulation must be increased as the terminal voltage is increased.

The higher voltage machine, if it is to be connected directly to the line, not only must have increased insulation to ground but also increased insulation between turns. Further, present tests would indicate that this increased turn insulation would need to be placed on other coils besides the terminal ones. This will lead to increased size of machines and may lead to mechanically weak coils because of the small percentage of copper in the coils.

It may be possible to decrease the voltage gradient by the use of condensers or lightning arresters tapped into the winding at various points, and while such devices are theoretically correct there is some question whether these may not lead to more trouble than the lightning. Means can also be taken to retard the front of the incoming wave and so reduce the percentage voltage on individual coils.

However, until considerably more research work can be accomplished on the effects of lightning and on means for combatting, we are not safe in assuming that it is possible to transmit at these increased voltages. Even after we have completed our work we may find that the increased cost of making the generator safe and the hazard of the auxiliaries will still make it desirable to transmit through transformers.

J. F. H. Douglas: I should like to compare Fig. 9A with Fig. 7A. I wish to point out the superiority of the flux distribution

in Fig. 9A. I should like Mr. Laffoon to comment on whether this theoretically superior construction in Fig. 9A results in such increased costs that it is impracticable from that point of view.

J. F. Calvert: To arrive at the electrostatic flux fields shown in Figs. 5A, 6A, 7A, 8A, and 9A, certain physical properties and boundary conditions had to be established. The following assumptions were made.

1. The insulating materials have a uniform specific inductive capacity in all directions.

2. There is not sufficient current flow (under 60-cycle conditions) to have any appreciable effect upon the potential field.

3. In Figs. 8A and 9A the conducting sheaths terminate at practically the same cross sections through the conductors.

4. The conductors are quite long so that the end effects do not have an appreciable effect on the flux and potential distribution within the central portion of the machine, so far as the conditions between any two adjacent pairs of conducting surfaces are concerned.

5. In determining the data given in Fig. 9A, there are equal capacities between each adjacent pair of conducting surfaces. This means that the inner conducting sheaths project further on the ends than the outer ones.

From assumptions 1 and 2, it may be written that,

$$V = \frac{e}{c}$$

or

$$\Delta V = \frac{\Delta e}{K} \; \frac{\Delta l}{\Delta a}$$

for a small volume

where

V = potential difference between two equi-potential surfaces

e = charge at end of electrostatic tube of flux

c = capacity

l = length along a flux tube

a = cross section of tube

K = specific inductive capacity.

From assumptions 3 and 4, it appears that the field between any adjacent pair of conducting surfaces need only be considered for unit distance in the axial direction of the machine. This reduces the problem to two dimensions and permits an easy graphical solution, and

$$\Delta V = \frac{\Delta e}{K} \; \frac{\Delta l}{\Delta w}$$

where w = width of the flux tube in the planes of the figures (5A to 9A). Then when $\frac{\Delta l}{\Delta w} = 1$, the field between two conducting sheaths may be drawn in curvilinear squares, as shown in the drawings. Along any flux tube, there will be equal potential differences between the surfaces which cut off curvilinear squares from this tube. Between two potential surfaces, there will be equal flux tubes represented by the space between the flux lines which cut out curvilinear squares.

This is the entire problem in Figs. 5A, 6A, and 7A, because the conducting surfaces occur only on the inside and outside, of the insulation. The potentials and gradients can be determined with reasonable accuracy from the drawings made on this basis.

In Figs. 8A and 9A it is found convenient to divide the space between adjacent conducting surfaces as described above for the entire insulation. Then the capacity for each space is

$$K \times \frac{\text{number of unit flux tubes}}{\text{number of unit potential differences}}$$

Where K = the specific inductive capacity, a unit flux tube is any size, and the unit potential difference is that which cuts a curvilinear square from the unit flux tube.

Since the total electrostatic flux from the inner conductor must reach the outside surface, the potential of each conducting surface may be computed and the potentials and gradients between these surfaces found as for Figs. 5A, 6A, and 7A.

The unit tubes between one pair of adjacent conducting surfaces may or may not be chosen the same as that between the next pair. It is more convenient to choose them so that there will be an even number of equal potential differences or squares between adjacent surfaces. However, if the flux tubes are chosen to be of the same magnitude throughout, there will be the same number of tubes crossing every potential line, yet there may be sharp changes in the boundaries of these tubes at the intermediate conducting surfaces. This is illustrated in the sketch accompanying this discussion, Fig. 2.

C. J. Fechheimer: It is well to consider what difficulties are associated with winding machines for voltages of the order of 33,000. The thought that comes to one's mind is that the wall thickness of the insulation becomes so great that there is but little space left for the copper. Thus, if the practise that has been followed in the past were to be continued in the future, a single wall thickness would be of the order of 0.5 in. If the copper width were equal to this, the slot width would then be 1.5 in. Although this is greater slot width than is usually employed, the copper would occupy only one-third, which would mean that the slots would have to be very deep or the machine considerably larger than at present. As the heat generated in the copper must be conducted through the insulating walls, with so great wall thickness it is necessary to operate at materially reduced watts per sq. in., which in turn implies larger section of copper, thereby again increasing the size of the machine. These factors then

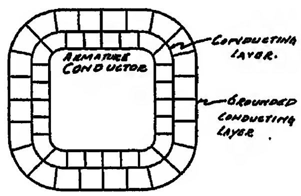

FIG. 2

lead to the questions: is it economically worth while to go to high voltages; if so, how can it be done practically? It is not my purpose to answer the first question as that has been discussed by Mr. Laffoon and others. I shall attempt, however, to consider the second and discuss some of the possibilities.

Coils which have been insulated for operating voltages of 13,200 have stood up to 140,000 volts before failure, indicating that if the insulation were not impaired after placing the coils in the machine they could withstand approximately 18 times normal voltage to ground if the neutral point is grounded. This would at first seem as an unnecessarily high factor of safety. During the process of placing the coils the insulation is frequently injured, and due to various uncertainties arising during manufacture, some coils fail at considerably lower voltages. Consequently the practise is to put on greater wall thicknesses than may seem necessary. Therefore, one important thing is to improve our processes of manufacture, so that greater uniformity will be obtained and the insulation less damaged when the coils are placed in the slots.

Another reason why our present wall thickness cannot with safety be much decreased, is that entrapped between layers of insulation are impurities, such as air, moisture, or other extraneous material. A tiny air pocket having a specific inductive capacity of unity in series with insulation having a specific inductive capacity of about 4 or 5 will be overly stressed with attendant internal corona. Such corona is productive of internal loss which heats the insulation and in all probability is the source of high-frequency oscillations at or near the peak of the voltage wave. These would not only tend to reduce the strength

of the insulation as a whole but if of long duration might cause failure. This then leads to the important conclusion that the insulation can be materially improved provided these voids be filled with some insulating material, preferably of values of specific inductive capacity corresponding to those of the main insulation and of approximately similar dielectric strength.

For many years engineers have struggled with these problems. Various impregnating compounds have been used, some with more success than others; while the voids have been reduced, but they have not been eliminated. The great successes achieved by the cable manufacturers in the use of oil-filled cables for operating voltages up to 132,000, indicates the possibility of this as one road for improvement; either employ insulation which is well treated with oil before the coils are put into the slots and possibly supplement by subsequent oil treatments, or run the entire stator in oil. The latter suggestion has been offered a number of times, particularly by A. B. Field. In the event that oil is used, it does not seem likely that the distance from the copper to the iron can be reduced. However, it seems that the net thermal drop from the copper to the slot sides for a given value of watts per sq. in. can be materially lowered, owing to the high thermal conductivity of the oil compared with that of occluded air, and of the possibility of some small internal convection currents within the oil. A stator which is operated with oil as the cooling medium would have the means of transferring the heat from the solid surfaces to the oil, far more readily than with air. The flow of the oil could be maintained readily by means of an external pump, and the heat abstracted by water in a suitable external heat exchanger. At present it does not appear that the mechanical difficulties of keeping the oil from leaking are unsurmountable. Oil-filled stators have been used in Europe on phase converters for electric locomotives and the reports so far have been that they have been eminently successful.

A stator which is operated in hydrogen has considerable advantage over one operated in air in that the corona discharge is not damaging to the insulation as far as we know at present. However, hydrogen has nearly the same specific inductive capacity as air and corona forms at substantially the same voltage gradient as in air. There is then still the possibility of internal losses and the likelihood of high-frequency oscillations being produced. With compact insulation it is doubtful whether all of the air trapped between layers is supplanted by hydrogen, and if it is supplanted a considerable period of time will be required. Nevertheless, a machine operated in hydrogen should be considerably safer at the high voltages than one operated in air because of the freedom of damage from external corona and because the fire risk is reduced owing to the absence of a supporter of combustion.

It is well to consider the high-voltage generator from the construction standpoint. The use of round slots has been proposed frequently, but they are objectionable because they are uneconomical in magnetic material, as the teeth become very narrow and are worked at high magnetic densities, and because a shoved-through coil construction is necessary. The idea of rounding the corners and preferably of making the ends of the copper semicircular as shown in Fig. 7 in Mr. Laffoon's paper, is excellent for two reasons: The voltage gradient is much more uniform, and the mechanical weakening of the insulation, which practically always accompanies the use of sharp corners, is materially reduced. The additional gains to be obtained by the use of conducting material at intervals as indicated in Fig. 8 is well worthy of consideration, although it is believed that the complication is hardly justified. It should be possible to embody the feature of rounding the coil ends, thereby reducing the wall thickness, and obtain more economical proportions. At the present time it is believed that grading of insulation, that is, the employment of materials of different specific inductive capacities, is not warranted, at least for voltages of the order of 33,000.

The scheme proposed by Messrs. Parsons and Rosen shown in Fig. 4 is not desirable for a number of reasons: there is necessarily a high thermal drop from the bull conductor to the outside; it is uneconomical from the standpoint of magnetic material; as it requires a shoved-through construction, the joints at the ends would be liable to be weak dielectrically; and the end windings are too complicated. The American practise of using rectangular open slots is the one to which we should by all means adhere.

Perhaps twenty years ago it was the practise in this country to use concentric windings as is still the practise in Europe. The concentric winding for high voltages has the advantage that only half as many coils are used and that the space occupied by the insulation between the two coils in the slot is eliminated. For high-voltage machines this space is appreciable. Nevertheless, the one coil per slot winding is undesirable for a number of reasons, for instance, that usually the wave form produced contains more ripples and the load losses are generally greater. With two coils per slot suitably chorded, the wave form is so close to a sine that the troubles, such as telephone interference, arising from higher harmonics, are practically eliminated.

P. Sporn: Mr. Laffoon's paper deals primarily with synchronous alternators and most of the principles laid down apply to synchronous alternators only and do not apply to synchronous condensers. I am referring, of course, to high-voltage synchronous condensers.

The problem that the synchronous condenser at high voltages presents to the designer is that of building a machine that will not only stand the normal and abnormal power-frequency stresses but also be able to stand impulses and surges, if it is to operate on a high-voltage bus from which overhead transmission lines are fed out.

The increased use of power makes 24,000, 33,000, 44,000, and 66,000 volts no uncommon voltages for what might be very accurately called distribution purposes. Many substations exist today where the lowest voltage existing in the station is a voltage of that order. To regulate these voltages properly the synchronous condenser is the logical tool to use, but the limitation of voltage that has been existing makes it a very expensive tool. In many cases, of course, a low voltage can be economically obtained by the use of a three-winding transformer but the three-winding transformer has the objection that it places definite limitations on the impedance arrangement possible between the three voltages, and makes it necessary very often to compromise on impedance arrangements to the great detriment of system stability. The use of a high-voltage condenser operating at the same voltage as the distribution bus, whatever it happens to be, automatically eliminates this difficulty. To make this feasible, however, it will be necessary to carry on more development work than has been carried on to date in the direction of obtaining either better impulse strength with materials that have been used heretofore in synchronous machines (although this is obviously difficult), or to go to entirely new materials. The development of oil-impregnated cable definitely points the way in one possible direction but very little has apparently been done in following up the lead. This seems regrettable.

It was thought for a while that the use of hydrogen-filled machines would solve this difficulty and we have a 15,000-kv-a. 24,000-volt synchronous condenser under construction on our system at the present time. However, while this makes possible the use of materials that would normally be difficult, if not impossible, to use and thus permits the obtaining of greater impulse strength than is possible with mica for example, it nevertheless falls short of meeting the necessary requirements as to strength. It would appear to be time to try new insulating materials operating in media other than gases.

R. B. Williamson: (communicated after adjournment) It should be noted that the 33,000-volt machine referred to in the paper has a graded insulation, *i. e.*, all parts of the winding are not provided with 33,000-volt insulation to ground. In the

machine described by Parsons and Rosen, one-third of the concentric conductors have 33,000-volt insulation to ground; one-third, 22,000; and the outer third, at the neutral, 11,000. On the other hand, the 22,000-volt machines so far built in this country, have all conductors insulated for 22,000 volts to ground. With the graded insulation it is possible to build 33,000-volt machines without making the slot space requirements for insulation too great. On the other hand, if all the conductors were insulated for 33,000 volts the space taken up by insulation would be so large that such a machine would be of abnormal design and excessively high cost. If, therefore, all conductors have to be insulated for the full voltage, the 33,000-volt machine is at a considerable disadvantage. Whether or not a generator voltage of 33,000 will be used in future in America, will depend very largely on the attitude of operating engineers as regards the use of graded insulation in large turbo generators. At present, many of these engineers feel that, with resistance or reactance in the neutral ground, conditions might arise where the 11,000-volt insulation on the ground end of the winding would not be sufficient to withstand the transient voltages met with under service conditions.

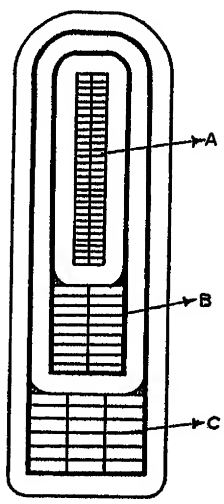

FIG. 3

The construction of the machine described by Parsons and Rosen is objected to in the paper on account of its not being well suited to the open-slot construction generally used in America and because of the arrangement of conductors not being as good from the heat-transfer standpoint as that of rectangular conductors. It may be pointed out that Messrs. Parsons and Rosen have proposed another arrangement, as shown in the accompanying Fig. 3. This would be well suited to open slot construction with diamond shaped end connections as used in this country. The high-voltage conductor A presents the largest area for transmitting heat through the insulation, and conductors B and C present areas of less amount, approximately proportional to the thickness of insulating wall. Thus where the insulation is thickest the watts per square inch transmitted through the insulation are least and it is possible to design a coil of this kind so that the temperature drop through the insulation will be approximately the same for all three sections. At the same time the current density may be as high in the high-voltage conductor as in either of the others. Metal sheaths can easily be inserted as shown by the heavy lines in order to insure equal voltage stress in the three sections of the insulation. This type of coil would suit open-slot design as well as coils of the usual type. The coil ends could be of diamond shape and the only additional complication would be in the coil connections required to carry out the grouping of the three voltage sections. So far as the graded insulation feature is concerned, it is equivalent to the concentric arrangement.

C. M. Laffoon: There is no disagreement with Mr. Wieseman in regard to the importance of obtaining a solid insulation free of air voids for high-voltage generator windings. It was the intent in the paper to give the results of insulation tests for treated cloth and mica tape, and not to advocate either one for general applications. Both are satisfactory insulation materials when properly applied. In part of the test coils the mica tape was vacuum-treated before applying, and in the remaining part it was not vacuum-treated. The coils were not vacuum-treated and impregnated after the insulation was applied. No wide difference was found in the test results, and average values were used.

In Mr. Alger's comments it was stated that the stresses on the end turns would probably be the same on the high-voltage machines as on low voltage. The statement made in the paper was intended to convey that with the leads and wiring around frame, connectors, and so forth, there would be less current to handle than with lower voltage machines, and the stresses would be reduced on these parts. A slight reduction of stress would be occasioned on the actual end turns, due to the fact that greater thickness of insulation is required, and the conductors would be placed a little farther apart. It was not intended to convey the understanding that a large reduction in stresses would be obtained in high-voltage windings.

In connection with the final potential tests for high-voltage windings, the writer proposed that present A. I. E. E. rules be followed for test voltages of 50,000 and less, and for higher test voltages than 50,000 that the time of test be reduced. Mr. Alger suggested the alternative proposal of increasing the time element and reducing the magnitude of the voltage. Such tests would be a satisfactory measure of the fitness of the insulation, but it would be necessary to obtain definite agreement in regard to the magnitude of the voltage reduction.

The writer agrees with Mr. Alger's statement, in regard to Parson's 33,000-volt generator conductor design, that on the basis of *same conductor surface area* the temperature rise should not be higher than for an American design, in which open rectangular shaped slots are used. The comparison in the paper is based on conductors having the same copper section and weight. The cylindrically shaped conductor is the most uneconomical shape from the standpoint of heat dissipating surface, and in order to obtain the same surface areas as for a rectangular shaped conductor it is necessary to use appreciably more conductor section and copper weight.

In reply to Professor Douglas' question concerning the electrostatic field, as shown in Fig. 9A, it is to be noted that the insulation design has not been worked out for practical application.

Mr. Schou raised the question in regard to the built-up type of insulation. If I understood him correctly, his proposition is to apply a certain per cent of the insulation and treat the coil and then apply another percentage, and so forth. In my original paper it specifies greater attention and consideration must be given to the building of the insulation and the application to the coils. That follows directly under such procedure indicated by that statement.

The writer is also indebted to Messrs. Sporn, Williamson, Calvert, Fechheimer, and Henderson for the valuable contributory discussions of the paper.

Double Windings for Turbine Alternators

BY PHILIP L. ALGER,* Member, A. I. E. E.
E. H. FREIBURGHOUSE,* Associate, A. I. E. E.
and D. D. CHASE* Associate, A. I. E. E.

Synopsis.—Large turbine alternators with two similar independent armature windings have recently been proposed, to permit the electrical segregation of bus sections in large stations without loss of synchronizing power. Several such generators have been installed, or are under construction, and it now seems that they will become of paramount importance in very large future stations. This paper explains the theory, and design limitations of these double winding generators, and describes their application in systems having different types of bus connections.

* * * * *

I. INTRODUCTION

A VERY recent and important development in the design of large steam turbine driven alternators is the use of two electrically independent similar armature windings. By loading the windings independently, the advantages of a higher generator reactance and hence lower fault currents are obtained, while yet retaining adequate synchronizing power. Also, by connecting the windings to adjacent bus sections of a sectionalized ring bus, the sections will be effectively separated by a high "through" reactance, thus limiting the current flow on faults, while still permitting power flow between sections, by virtue of the transformer action between the two windings.

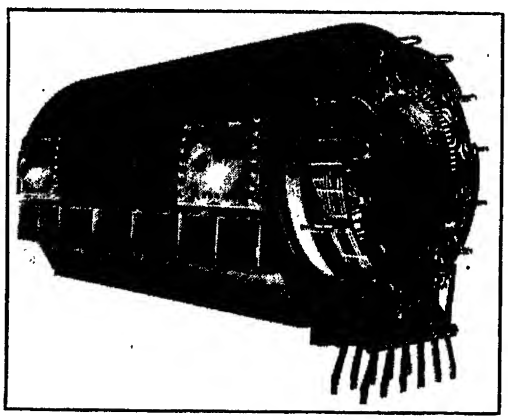

FIG. 1—WOUND STATIONARY ARMATURE, WITH WELDED FRAME, FOR DOUBLE-WINDING GENERATOR

83,333 kv-a., 1800 rev. per min., 13,800 volts

These characteristics permit the elimination of bus reactors, and a reduction in the required circuit breaker capacity, so that the double winding generator is likely to be extensively utilized in large stations of the future.

The first unit of this type to be installed is the 60-cycle, 83,333 kv-a., 13,800-volt generator, shown in Fig. 1, which has been in operation since the latter part of September 1929, in the Cahokia station of the Union Electric Light and Power Company at St. Louis. The second is the 25-cycle, 160,000-kv-a., unity power factor, 11,400-volt, generator of the New York Edison Company, which was placed in service early in October. Several others are now under construction.

Multiple circuit armatures have been commonly used for many years, to reduce the currents individual conductors are required to carry, but their circuits are not suitable for independent loading since any inequality of

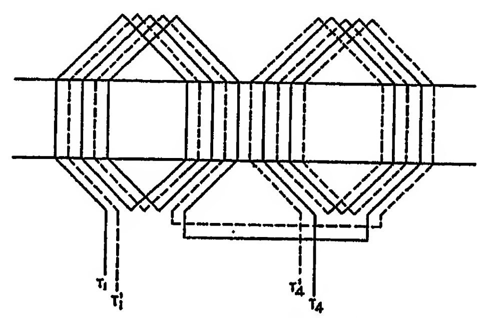

FIG. 2—SCHEMATIC DIAGRAM OF ALTERNATE SLOT DOUBLE-WINDING GENERATOR

Fractional pitch, one-phase per pole indicated for each winding

circuit currents normally gives rise to an irregular flux distribution, causing extra power losses and abnormal mechanical stresses. Only two types of winding are considered suitable for the purposes mentioned above, the alternate slot type, shown in Fig. 2, and the split belt type of Fig. 3. In the former, the two independently loaded circuits lie in alternate slots, with no two coil sides of different circuits lying in the same slot.

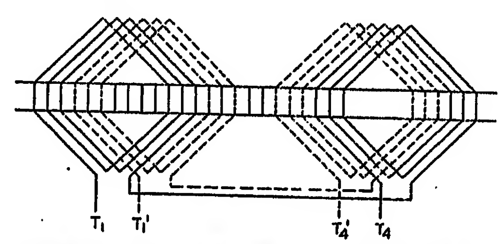

FIG. 3—SCHEMATIC DIAGRAM OF SPLIT PHASE BELT DOUBLE-WINDING GENERATOR

Fractional pitch, one-phase per pole indicated for each winding

In the latter, each phase belt of a single winding machine is divided into two approximately equal portions, of which one is assigned to each circuit, and the sequence of half belts in each circuit is so selected as to give perfect circuit and phase balance, while minimizing the

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number of slots carrying coil sides of different circuits. Either type of winding can be loaded unequally up to the limit allowed by armature heating, without important disturbance of the symmetry of the magnetic fields, and without introducing unusual stray losses or mechanical forces.

The alternate slot type gives perfect magnetic symmetry with unequal loading, but has its transfer reactance considerably reduced by saturation under excessive fault currents. The reactance of the split belt type is less affected by saturation, but this winding gives an appreciable dissymmetry of the magnetic field and slight extra losses with unequal loading. The latter type is recommended for general use, as it enables the minimum of reactor capacity to be used, with no real sacrifice in performance. The two machines mentioned above, however, have alternate slot windings.

The alternate pole type of winding is distinctly undesirable, as it gives low "through" slot reactance, unless approximately two-thirds pitch is used, and it gives large stray losses with unequal loading. Also, the magnetic forces on the end windings during a short circuit are much greater than with the other types of winding.

II. Advantages of the Double Winding

The advantages in station design and operation, to which the new type of armature winding gives rise, may be grouped under the following headings:

(1) It reduces the magnitudes of the short circuit currents, which the circuit breakers are required to open under fault conditions, without increasing the number of breakers required.

(2) It maintains higher bus voltages during fault conditions.

(3) It reduces to one-half the magnitude of normal current, which the breakers and disconnecting switches must carry.

(4) It permits the elimination of bus reactors between adjacent bus sections.

(5) It reduces the capacity of generator reactors required.

(6) The decrement of the d-c. component of the short circuit current is approximately doubled, because the single winding supplying current to a short circuit has twice the resistance of a single winding machine of the same total output. On the other hand, the decrement of the a-c. component of the short circuit current is slightly reduced, because of the greater reactance of one winding, as compared with the reactance of the full output single winding machine. The increased rate of decay of the d-c. component may be of considerable importance when high-speed switching is employed.

There are certain limiting or offsetting features, on the other hand, which must be considered in evaluating the net gain due to the new double winding.

(1) It imposes certain limitations on the design of the armature winding, which are reflected in a slight increase in generator cost, without, however, affecting reliability in any manner. More connections are required than for the standard generator winding, but all are normally made on the same end.

(2) The saturation of the "through" reactance, due to excessive currents flowing between bus sections through the two windings, reduces its value for the reduction of fault currents.

(3) The kv-a. that can be transferred along the bus are limited. If the two windings are unequally loaded, the heating limits of full balanced load will be obtained in one winding with less than rated output from the generator. If, however, the ratio of loads in the two windings is kept less than 1.2, full load can be carried without exceeding the normal armature temperature rise by more than about 5 deg. cent. If one winding only is loaded, and the other is disconnected, approximately 60 per cent of rated current for the entire generator can be carried on the loaded winding. However, this difficulty due to unequal circuit loading can be overcome by means of a balancing transformer, which will equalize the current and power between the two windings, even though the bus sections may have considerably different vector voltages.

The connections of the double winding generator, and of the station buses, by which the advantages are obtained, are explained, and the advantages themselves are evaluated for each of the usual bus arrangements, in the sixth section of the paper.

These limitations will be considered in the following sections, though a consideration of the balancing of load mentioned under (3) will be reserved for discussion in a future paper, after the methods and devices required have been more fully studied.

III. Equivalent Circuit of the Double Winding

A satisfactory double armature winding must fulfill two principal conditions:

(a) The two circuits must be capable of operating independently, or jointly, up to their heating limits, without magnetic unbalance, excessive losses, or abnormal mechanical stresses.

(b) The two circuits must be so interlinked that they can act as the two windings of a high-reactance transformer in transferring power from one bus section to the other, while yet limiting the current flow on faults.

In order to meet condition (a), it is necessary that each circuit contain coil sides under every pole, as otherwise there would be excessive magnetic dissymmetry, with unequal current loading. To meet (b), the circuits should be arranged to have as little mutual leakage flux as possible. It is also desirable, to avoid saturation of the through reactance flux leakage paths, that as many as possible of like slots be grouped together. The first condition can be met at the expense of the second, by arranging the two circuits in alternate slots, as in Fig. 2; while the second condition can be met at the expense of the first, and also at a sacrifice

with respect to condition (a) by arranging the two circuits under alternate poles. It is not convenient to arrange the winding in alternate pairs, or triplets, of like slots, because there is normally only space available for connections to approximately six phase belts per pole, and such a winding would ordinarily result in nine or more belts per pole. Neither of the two possibilities mentioned is as flexible in design as desirable, since only certain combinations of slots and winding pitches can be used. By compromising between them, and using the split belt winding of Fig. 3, approximately 80 per cent of the slots can be made to carry in-phase, or nearly in-phase, currents, while yet like slots occur in groups, and considerable flexibility is retained. For these reasons, the split belt winding is preferred for nearly all cases.

In a double winding of the alternate slot type, the end windings are so closely interlinked that the end leakage fluxes may be assumed entirely mutual, without important error. With the split belt winding, approximately one-quarter of the end leakage is considered to be purely self inductive, and the rest mutual to the two circuits, while with an alternate pole winding nearly all the end leakage is self inductive. The slot reactance of each circuit of an alternate slot winding is entirely self inductive, but only about 80 per cent of the slot reactance of a split belt winding is self inductive, the remainder being mutual to the two circuits. An alternate pole, full pitch, winding has about three-quarters of its total slot reactance mutual; but if the winding is two-thirds pitch, the slot reactance is all self inductive, the proportions of self and mutual varying linearly with pitch between these extremes.

The zigzag leakage reactance varies in the same general way as the slot reactance, though the relations are more complicated in this case. Its small value, however, does not warrant a careful analysis here. The fundamental air gap flux, due to the armature reaction of either circuit, links each circuit equally, so that it is entirely mutual.

On this basis, the theory of the double winding generator is found to be the same as that of a symmetrical three-winding transformer, which has been treated by various writers,[1, 2] and its electrical performance may be predicted by means of one of the equivalent circuits of Fig. 4. The usual values of the individual elements of the reactance are indicated on the circuits in terms of the conventional values X_S, X_T, and X_E of the slot, zigzag, and end leakage reactances of the complete winding, formulas for which have been given in a previous paper by one of the present authors.[3] There are so many possible winding arrangements, especially when fractional slots per pole per phase are used, that it is difficult to make any general rule for the division of the slot reactance into its mutual and self inductive parts. By counting the numbers of slots carrying through transfer currents, that are 0, 60, 120, and

1. For references see Bibliography.

180 deg. out of phase, respectively, in the upper and lower coil sides, and adding the corresponding elements of slot reactance of each kind, it is not difficult to find the correct values for any given case.

For transient conditions, the synchronous reactance must be replaced by the transient, or subtransient, reactance, depending on whether the conditions a half second or so after, or at the instant of, a disturbance are to be considered.

The circuit of Fig. 4 is not exactly correct, because in reality there is no physical connection between the two windings, and all the interchange of currents between them occurs by transformer action. The current in one winding is, therefore, greater than the other by an

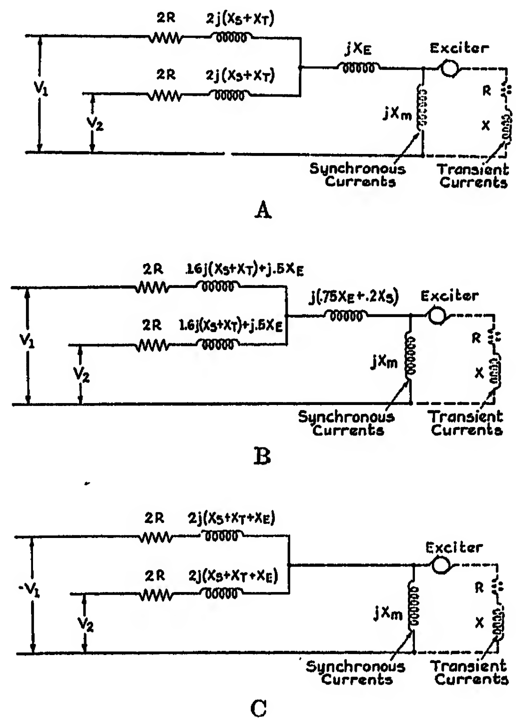

FIG. 4—EQUIVALENT CIRCUITS OF DOUBLE-WINDING GENERATORS

A. For alternate slot winding
B. For split belt winding
C. For alternate pole 2/3 pitch winding

amount sufficient to magnetize their mutual reactance flux path, when power is transferred between windings. As this mutual reactance is large under steady state conditions (about eight times the reactance of either branch), but much smaller under transient conditions, the error due to neglecting the magnetizing current component is negligible in synchronous operation, but may be appreciable under transient conditions. In the latter case, however, it is on the safe side, as it causes the apparent through reactance to be slightly lower than the actual.

While tested values of reactance, at low currents, agree well with the values calculated in accordance with the above methods, the reactance decreases under high currents, due to saturation of the slot leakage flux

paths. There is negligible saturation when both windings carry equal and in-phase currents, since in that case the leakage paths have large areas and relatively short lengths of iron as compared with air. When the windings carry equal and opposite currents, however, as occurs in practise when current is transferred from one side of the machine to the other, the saturation may be very marked. It is, therefore, important to calculate its effects.

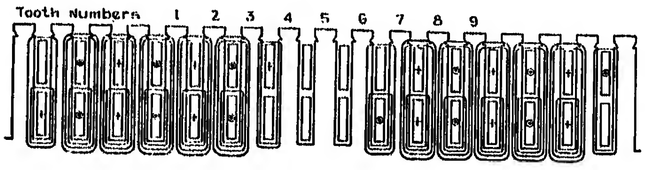

Fig. 5—Alternate Slot Double Winding Through Leakage Flux Paths for Single-Phase Line-to-Line Short Circuit

Assuming equal incoming and outgoing transfer currents, the current distribution, and the corresponding slot leakage fluxes, on a single-phase line-to-line short circuit will appear as shown in Fig. 5, for the case of a slot 9 per pole, 8/9 pitch, alternate slot winding. With this type of winding, the leakage fluxes due to adjacent slots alternate in direction, so that the resultant effect is to make the total leakage flux pass through the root of every tooth. The four teeth in the center of the phase belt, numbers 1, 2, 8, 9, carry

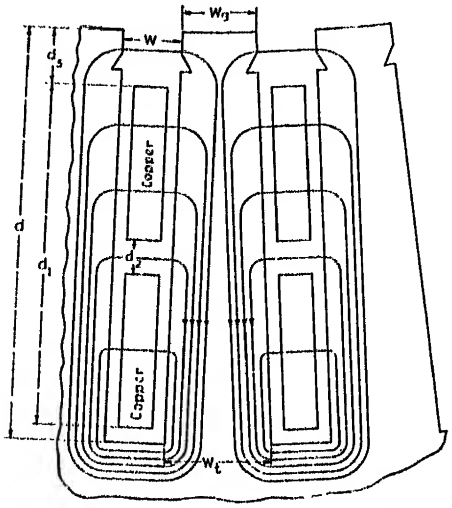

Fig. 6—Diagram of Stator Slot and Unsaturated Flux Leakage Paths

maximum flux, those at one edge of the phase belt, numbers 3 and 4, carry, respectively, about 0.65 and 0.15 times as much, and those at the outer edge, numbers 6 and 7 carry, respectively, about 0.35 and 0.85 as much. These coefficients are based on normal slot proportions and take account of the fact that the leakage flux due to a lower coil side is about 7/3 as much as that due to an upper coil side. At ⅔ pitch, there will be only two teeth of the first type, one each of the other types, and two more of each of two intermediate types. Hence, the effect of short pitch is to reduce the amount of saturation and make it more gradual, without, however, affecting the point at which it first begins.

The actual magnitude of the flux density in the teeth of the first type, between slots carrying in-phase currents, is readily calculated from a knowledge of slot reactance theory,[3] as described in Appendix A.

The leakage flux paths in the unsaturated condition are shown in more detail in Fig. 6. As saturation of the tooth root is reached, the flux paths approximate to those in Fig. 8, under which condition the slot leakage reactance is approximately one-third as much as in the first case. As saturation continues still further, the teeth become saturated throughout their whole length, and the reactance approaches a final value, corresponding to paths entirely in air, which is about 15 per cent of the original value, but this final condition is never approached in practise.

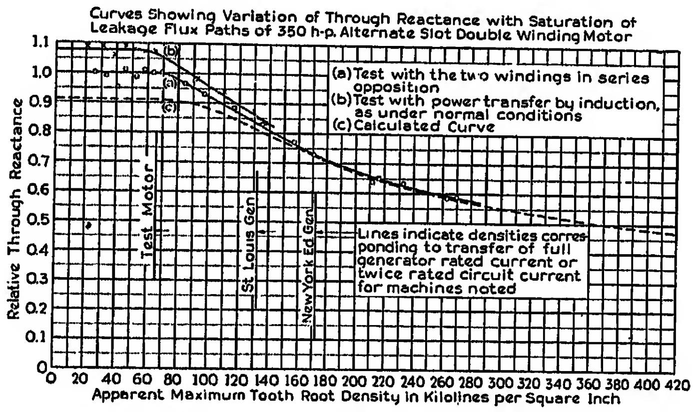

Fig. 7

IV. Tested and Calculated Values of Reactance

In Fig. 7 are shown test curves of the through reactance of a 350-hp., 25-cycle, 8-pole, 0.8-pitch, alternate slot, double wound motor, plotted as functions of the calculated maximum tooth density. Test (1) was made by connecting the two circuits of one phase in series opposition, with the rotor stationary, and applying a single-phase normal frequency voltage across them. R. m. s. values of current, voltage, and power were read, and the reactance so determined was plotted against the apparent maximum tooth density calculated by Equation (4) of Appendix A. Test (2) was made with one winding short circuited, and with the rotor at synchronous speed, by applying three-phase voltages to the other winding. In this case, the induced current was only about 0.9 of the impressed current, due to the magnetizing current component of the latter. The apparent primary reactance determined from this test was plotted against the density corresponding to the average of the two currents. The apparent secondary reactance, or primary reactive

voltage divided by secondary current is, of course, about 10 per cent larger. The calculated through reactance for this motor, determined by methods explained in Appendix A, is shown by curve *c* of Fig. 7. The tests confirm the saturation with increasing current, and the existence of an approximate limiting value of about 0.3 the initial, indicated by the calculations.

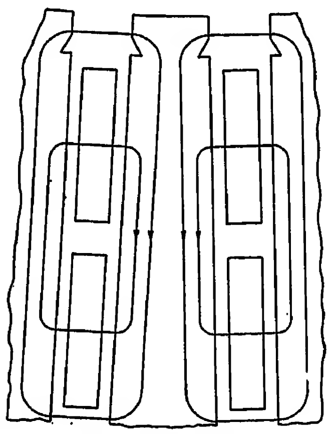

Fig. 8—Diagram of Slot Leakage Flux at the Limiting Condition of Saturation

In Fig. 9 there are shown tested and calculated values of the through reactance of a model alternate slot, double wound turbine alternator, rated 260 kv-a., 60 cycles, 4 poles, 250 volts. The calculations were made by the same method described in Appendix A. The tests in this case, however, were made in several different ways. At low currents, the through reactance was measured by connecting the two windings in series opposition, with the rotor removed, and measuring the 60-cycle impedance. At higher currents, the reactance

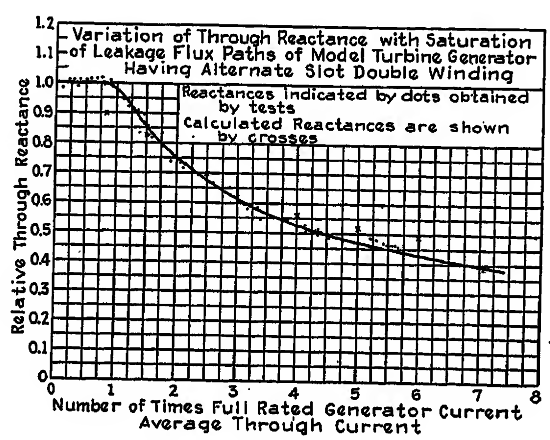

Fig. 9

was measured by operating the machine at no load at different voltages, short circuiting one of the windings, and taking oscillograms of the resulting currents and voltages. Tests were made both with the other winding opened and with the other winding connected to an infinite bus through varying amounts of reactance. The through reactance was calculated by dividing the average of the observed peak currents in the two windings into the observed peak voltage across the unshorted winding. The values so obtained agreed closely whatever point on the decrement curve of the short circuit current was taken and whatever the connection of the unshorted winding. To put the reactance values on a common base, however, it was necessary to plot them against half the algebraic difference of the currents in the two windings, since saturation of the leakage paths is produced only by the through current, and not by the in-phase components of the two winding currents.

In this case again, the tested and calculated values agree fairly well, although at very low currents the tested value of recatance is somewhat more than the calculated. This difference is ascribed to components of the zigzag leakage flux in the solid rotor, which saturate at very low currents.

As mentioned above, and as pointed out in the Ap-

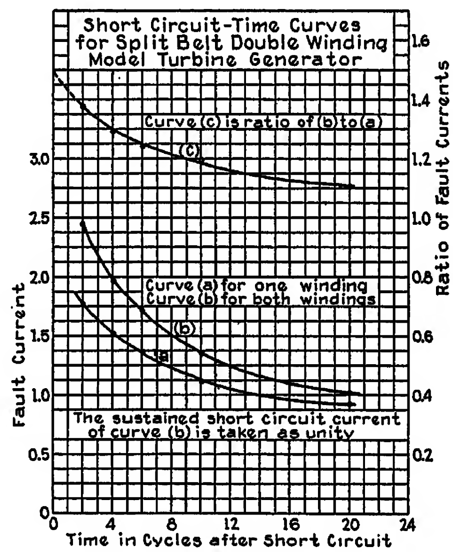

Fig. 10

pendix, twice as much current in one winding alone as through current is required to produce saturation of the slot leakage flux paths. Also, as explained in the Appendix, the limiting asymptotic value of slot reactance, approached when one winding alone carries current, should be about 63 per cent of the initial value, instead of about one-third of the initial value, as is the case when the currents in the two windings are equal and opposite. Tests were made to investigate this point, by short circuiting first one winding alone and then both windings of the model turbine generator, and comparing differences in the subtransient reactances obtained with the expected amount of additional slot reactance. The results were inconclusive, however, as the uncertainty of the test values of initial currents read from the oscillograms was too great. The subtransient reactance of any normal turbine generator decreased markedly with increase in the short circuit current, due to saturation of the rotor leakage flux

paths, so that the presence of a similar degree of saturation in the additional slot leakage reactance, when one winding of a double winding generator is short circuited, is not important. The tests showed, however, that the subtransient reactance of a single winding generator varies approximately in the ratios of 1.6 to 1.2 to 1.0, when the initial short circuit current has values of 1, 4, and 10 times normal, respectively.

So far, the test results and calculations have been confined to the alternate slot type of winding. For the split phase belt type of winding, the calculation of saturation effects is more complicated, since the flux leakage paths encircling the outer conductors of each half phase belt saturate earlier than those linking the inner conductors. In general, with a winding of approximately 5/6 pitch, the currents in the slots of adjacent half phase belts are approximately 30 deg. out of phase, so that when one winding current is a maximum the other is only 0.866 times its maximum value. Also, the slots adjacent to phase belts carrying in-phase currents in the top and bottom coil sides normally contain coil sides carrying currents out of phase by 60 deg. Hence, the total values of the currents in slots adjacent to phase belts carrying in-phase currents are normally only 0.866 times as great as the total slot currents within the phase belt. Thus, at the moment of maximum current in the phase belt carrying in-phase currents in the top and bottom coil sides, the currents in the adjacent slots are only three-quarters as great. It is thus apparent that normally 4/7 of the area of each end tooth is available for carrying leakage flux, instead of only 50 per cent of the area, as is the case for the alternate slot winding. Also, the slot leakage flux paths, which

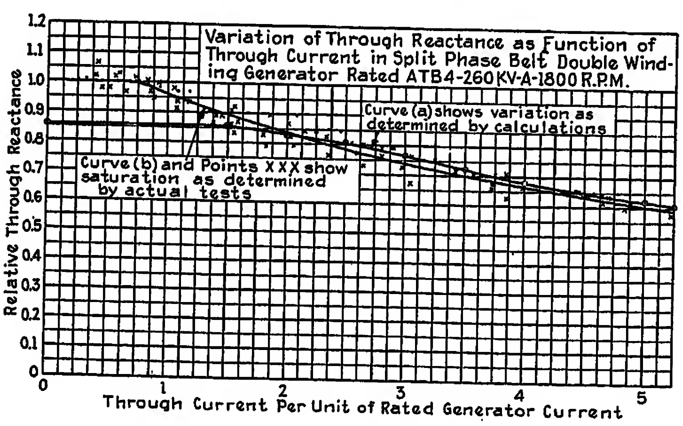

Fig. 11

pass through the end teeth of a half phase belt, cross all the intermediate slots, so that the ratio of length of iron path to length of air path is reduced by a factor equal to the number of slots in the half phase belt, as compared with the alternate slot winding.

Taking into account these factors, curve *a* of Fig. 11, of calculated through reactance against the through current for another model alternator with a split phase belt winding, was plotted. The test results shown in curve *b* agree with the calculated results to about the same degree of accuracy as was found for the alternate slot case of Fig. 9. The tests confirm the less amount of saturation for the split phase belt winding, as compared with the alternate slot winding, indicated by the calculations.

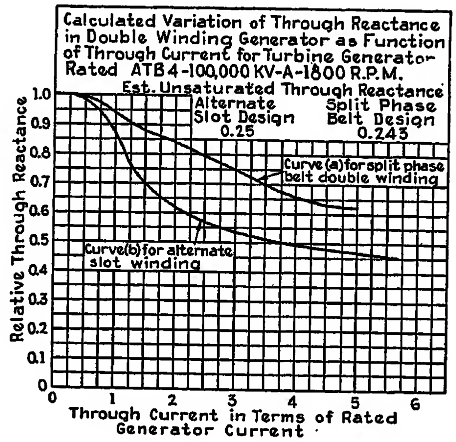

Fig. 12

In Fig. 10 are shown the results of short circuit tests on the split phase belt double winding model turbine generator. Curve *c* gives the ratio of the fault current when both windings are short circuited to that when one winding alone is shorted. It indicates that, disregarding the through current supplied by other machines, the initial fault current of a single circuit generator is roughly 1.5 times that of a double winding generator. The plotted points in Fig. 10 are the averages of the symmetrical r. m. s. currents read from oscillograms of three-phase short circuit tests taken at four different voltages, so each represents twelve observations. The actual current-time curves *a* and *b* for the different voltages varied considerably, due to saturation, but curve *c* was not noticeably affected.

Large alternators have relatively deeper slots and much higher current loadings than small machines, so that the effects of saturation become worse as the size of the machine increases. It is, therefore, unsafe to use the curves of Figs. 9 and 11 directly in practical calculations. Using the same methods as in calculating the curves of those figures, however, Fig. 12 has been prepared, which shows the expected variation of through reactance with through current for a 100,000 kv-a. generator, the upper curve representing the split belt winding, and the lower the alternate slot winding. In practise, it is to be expected that the through current on the most severe faults may be approximately three times the full generator output. The curves show that at this current the through reactance will saturate to about 0.75 of its initial value with the split belt winding, but to about 0.53 with the alternate slot winding.

V. Effects of Unequal Loading of the Two Windings

It is important also to know how the operating characteristics of the machine vary when the two windings carry unequal currents, especially in respect to stray load losses and the magnetic forces on the end windings.

The irregular arrangement of the conductors in each winding by itself results in a considerable departure of the armature m. m. f. from a sine wave, and this in turn produces high-frequency fluxes in the solid rotor surface. These fluxes naturally produce surface losses in the rotor, and cause additional heating of the field winding. Since, however, the limit of the armature heating is reached with about 0.6 of the full rated generator current, when one winding is open, the field current required under this condition is less than normal, and so there is a margin of field heating available to be taken up by the additional stray losses. There are also additional losses in the end structure, especially with the alternate pole type of winding.

The magnitudes of the stray losses in the rotor surface can be roughly calculated, or at least compared between different machines, by calculating the r. m. s. value of all the harmonics of the m. m. f. wave. This has been done in the case of four separate machines, on which test values of the stray load losses obtained with one winding carrying current and the other open circuited are available. The test values are shown in Fig. 13, from which several interesting conclusions can be drawn.

Tests on the alternate slot wound 350-hp. synchronous motor showed no appreciably greater loss with one than with both windings for the same total current, though curve *a* of Fig. 13 shows an appreciable increase for the similarly wound model generator. This indication that the same type of dissymmetry causes greater losses with the solid steel rotor construction than with the laminated pole and copper squirrel cage construction, is confirmed by comparing curves *d* and *c* for alternate pole wound machines of these types. The sums of the squares of the calculated r. m. s., m. m. f. harmonics for the alternate slot, split phase belt, and alternate pole windings tested are equal to 0.013, 0.034, and 0.092 respectively. The increased loss of the split belt over the alternate slot winding obtained by comparing curve *b* with *a* is small, but the extra loss with alternate poles shown by curve *d* is far more than justified by the amount of its harmonics, thus confirming the conclusion that there is a large loss in the end structure in the latter case.

In the alternate pole winding, when one winding alone carries current, the end leakage flux is bunched in alternate pole pitches, creating not only local concentration of flux in the armature shields and flanges, but also eddy currents in the rotor retaining rings. The machine for which curve *d* of Fig. 13 was obtained had magnetic retaining rings and armature flanges, so that the results are pessimistic, but in any case it would be difficult to keep the end losses down with this type of winding.

The load loss of the split belt winding, with one winding carrying half the full output, is somewhat less than the normal stray load loss of the machine, so that under this condition of operation the total heating of the machine should be less at all points than when full output is carried equally divided between the windings. This conclusion has been confirmed by heat runs on the model generators, which have shown differences of only 3 or 4 deg. cent. in field temperature rise, when half output is carried on one winding, as compared with carrying one-quarter the output on each winding.

In practise, when the two windings carry unequal currents, the additional stray load loss will always be less than the values shown, so that there is no question of the suitability of the split belt type of winding in this respect.

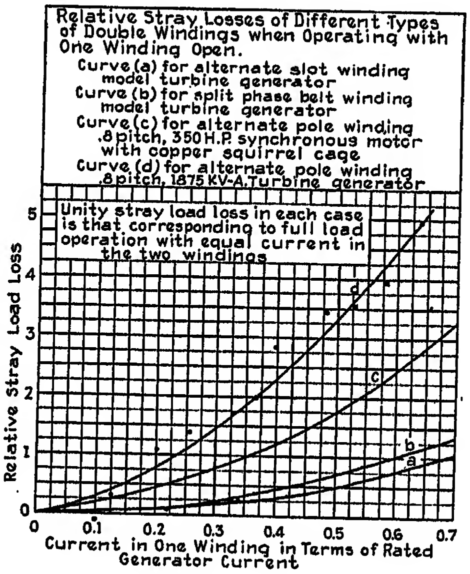

Fig. 13

The magnetic forces on the end windings are greatest on the end conductors of phase belts, since these are both attracted by the remainder of the phase belt and repelled by the out-of-phase current in the adjacent phase belt. Since the upper and lower layers of the end conductors are directed approximately at right angles to one another, there is very little magnetic force on either layer, due to the other. We may, therefore, estimate the relative forces with different kinds of windings by considering only one layer of the winding.

In general, the force on any conductor is proportional to the product of the current in that conductor by the intensity of the magnetic field at its center, due to all the other currents in the vicinity. It is a simple matter to add up the flux densities due to the neighboring conductors considered separately, and for a given current the force will be proportional to this sum. This point of view shows that the force per inch of conductor length is not affected by the winding pitch, although, of

course, the total force is greater the longer the length of end connection.

For the case of a 6 slot per pole per phase winding, the relative end winding forces in the four types of winding are compared in the following table. The left hand column gives the relative force, assuming a given current flows in one circuit, the other circuit being open. The right hand column gives the force when the same current flows in one winding and out the other. In both cases, the force with a standard single circuit winding carrying the same current is taken as unity. Three-phase currents are considered in all cases.

Type of winding	Relative end winding magnetic forces	
	One winding only loaded	Windings carrying equal and opposite currents
Normal single circuit	1.0	....
Same but carrying 0.7 current	0.5	0.5
Alternate poles	0.95	1.25
Alternate slots	0.4	0.25
Split belt	0.6	1.1

Since the maximum through current may be safely taken as less than three-quarters of the maximum single winding current, the left hand column may be taken as an approximately correct indication of the relative forces to be met with in practise. It may be expected in practise that any double winding machine with a fault on one winding only will deliver about 0.7 as much instantaneous current as the corresponding single winding machine, so the proper comparison of maximum forces is made by taking the current in the double winding machine as 0.7 that in the single winding machine, as shown in the second row of the table. On this basis, it is seen that the relative forces to which the end windings are subjected in practise for the single circuit, alternate pole, alternate slot, and split belt windings are about in the ratios of 1 to 1.9 to 0.8 to 1.2, respectively. Clearly, the split belt winding is satisfactory from this point of view, while the alternate pole winding is definitely inferior to the other types.

VI. Applications of Double Winding Generators

The advantages resulting from the use of double winding generators in large stations may best be shown by comparing the fault currents and the amount of protective equipment required with the usual systems of bus connections, using single and double winding generators. Five arrangements will be considered, as illustrated in Figs. 14 to 18 inclusive:

1. The standard ring bus with bus reactors (Fig. 14)
2. A ring bus with generator reactors, utilized also as bus reactors, with single winding generators (Fig. 15)
3. A ring bus with double winding generators, using alternate slot arrangement of windings (Fig. 16)

3A. A ring bus with double winding generators, using split belt arrangement of windings (Fig. 16)

4. A star bus with single winding generators (Fig. 17)
5. A star bus with double winding generators using split belt arrangement of windings (Fig. 18)

All the system diagrams shown are simplified by showing only a single bus, although a double bus arrangement is standard in the United States. The characteristics of the five systems, using 150,000-kv-a., 13,800-volt generators are compared in the accompanying tabulation, the per unit subtransient reactance of the two windings in parallel being taken as 0.113, of which 0.043 is mutual for the alternate slot case. In making the calculations for this comparison, the double bus was used throughout, and it was assumed in all cases that there were no external power ties to the system, although it is usual for several stations to be interconnected. This assumption makes the advantages shown for the double winding generator appear less than they really are, as any additional current supplied to a fault by the connected stations increases the importance of any means of limiting the current supplied by the station itself. Generator reactors, or their equivalent, have been used in all cases, in order to secure the advantages of a higher bus voltage and lower fault currents during faults in the generators themselves, or their connecting cables, and to reduce the currents supplied by the generators to external faults.

The important characteristics which affect the choice of generator and bus connections are the magnitudes of the fault currents, and the numbers and sizes of circuit breakers and reactors required to permit flexible operation and give adequate protection. Accordingly, these quantities have been calculated for each of the five systems, and are shown in the table. The first five lines of the table were compiled on the basis of unlimited ampere capacity of the circuit breakers. The 6300-ampere breakers required in three of the systems are larger than desirable, however, as most operating companies prefer to use 4000-ampere breakers, or smaller, if possible, and as the manufacturers prefer to limit the sizes to their present developed lines. The largest breakers so far built by the General Electric Company are, for the double tank per phase type, 6000 amperes, and for the single tank per phase type, 5000 amperes. The limit of interrupting duty for oil circuit breakers at present is about 2,000,000 kv-a. While larger breakers can be developed, their cost will be high, and so it is of considerable economic importance to keep the present standard sizes.

For this reason, the remainder of the table has been compiled on the basis of 4000-ampere breakers being used throughout. This considerably reduces the maximum kv-a. that can be transferred along the bus for Cases I and II, as indicated by the eighth line of the table, unless additional breakers operated in parallel are employed, as shown by lines 6 and 7. In discussing the characteristics shown for the different systems, each case will be considered separately.

Case I. The standard double ring bus of Fig. 14 superseded the straight bus in 1909, and is still used by most companies. Its original adoption was due to its limitation of the fault currents, and the increased system reliability it afforded. It is still considered a standard because of the flexibility it allows in transferring loads from one bus section to another. However, with the advent of generator of such large size as the 150,000 kv-a. machines considered here, the same difficulty of excessive fault currents appeared with the ring bus and its sectionalizing reactors as originally appeared with the solid bus. The table shows that the instantaneous symmetrical kv-a. delivered to a fault are nearly 2,500,000. Also, with the increasing demand for these large generating units of very high efficiency, the normal full load currents to be carried by the breakers, are becoming excessive; in the case shown 6300 amperes are required. A third important disadvantage of this system is that the generator on a faulted bus section has no synchronizing power with the rest of the system. The voltages on adjacent bus sections drop to much lower values than with the other systems, so that a bus section disturbance is really a system disturbance as well.

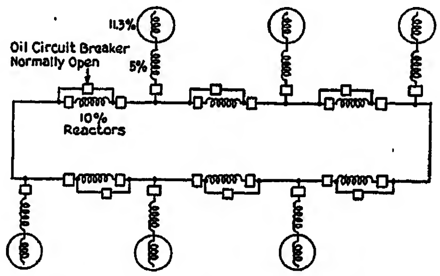

Fig. 14—Standard Ring Bus System. Case I

Case II. This (Fig. 15) is a modification of Case I, in which the generator is connected to the bus section between two reactors, thus making each reactor serve both as a bus and as a generator reactor. The energy of the unit is divided so that the normal voltage drop in the reactors, and the normal current carried by the breakers, are small. If it is desired to transfer the full capacity of a generator along the bus, however, the limitation of excessive current ratings, 6300 amperes for the breakers, is met with again. This system is really a half way step between systems 1 and 3.

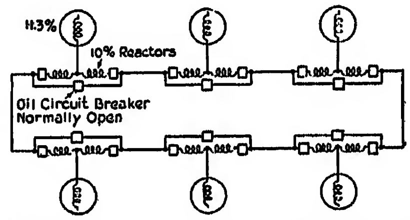

Fig. 15—Modified Ring Bus System with Standard Generators. Case II

Case III and III-A. In this system (Fig. 16) double winding generators are used, with each winding connected to a different bus section, so that the only power transfer along the bus is due to the transformer action

TABULATION FOR A THREE-PHASE FAULT ON THE BUS IN TYPES OF STATIONS AS SHOWN IN CASES I TO V, FIGS. 14 TO 18 OF THE COMPLETE PAPER

All Breakers and Reactors as Listed per Generator are for Double Bus Generators Rated ATB-4-150,000 Kv-a.-1800-13,800-Volts 0.85 Power Factor-6280 Amperes

	Case I Fig. 14	Case II Fig. 15	Case III Fig. 16	Case IIIA Fig. 16	Case IV Fig. 17	Case V Fig. 18
Limit of kv-a. transfer along bus	150,000	75,000	15,000	15,000	150,000	75,000
No. of breakers per generator	8	6	6	6	6	10
Ampere rating of oil circuit breakers	6,300	6,300	4,000	4,000	6,300	4,000
No. of reactors required	3	2	2	2	2	4
Rating of reactors	6,300	6,300	4,000	4,000	6,300	4,000
Preferred arrangement, limiting all breakers and reactors to 4000-ampere rating						
No. of breakers required	16	12	6	6	12	10
No. of reactors required	6	4	2	2	4	4
Limit of kv-a. transfer along bus	95,000	20,000	15,000	15,000		
No. of breakers per generator	10	6	6	6		
Ampere rating of breakers	4,000	4,000	4,000	4,000		
No. of reactors required	4	2	2	2		
Ampere rating of reactors	4,000	4,000	4,000	4,000		
Instantaneous symmetrical kv-a. to fault	2,470,000	1,660,000	1,370,000	1,216,000	1,900,000	1,200,000
Sustained kv-a. to fault	985,000	780,000	580,000	560,000	830,000	660,000
Instantaneous r. m. s. symmetrical amperes	103,000	69,500	57,000	51,000	79,500	50,000
Sustained fault amperes	41,200	32,600	24,300	23,500	34,800	37,700
Percentage instantaneous voltage on faulted bus	0	0	0	0	0	0
Percentage instantaneous voltage on bus next to fault	51	71	89	92	78	88
Percentage instantaneous voltage on 2nd bus from fault	74	91	99	99		
Percentage instantaneous voltage on 3rd bus from fault	80	96	99	99		
Percentage instantaneous voltage on synchronizing bus					65	80
Percentage sustained voltage on faulted bus	0	0	0	0	0	0
Percentage sustained voltage on bus next to fault	25	40	54	58	48	60
Percentage sustained voltage on 2nd bus from fault	39	59	79	81		
Percentage sustained voltage on 3rd bus from fault	43	65	86	87		
Percentage sustained voltage on synchronizing bus					40	54
Instantaneous sym. kv-a. to synchronizing bus fault					3,420,000	3,420,000
Sustained kv-a. to synchronizing bus fault					1,200,000	1,200,000
Instantaneous r. m. s. sym. amps. to synchronizing bus fault					143,000	143,000
Sustained r. m. s. sym. amps. to synchronizing bus fault					50,000	50,000

between the two windings of a single generator. Generator reactors of 10 per cent are used in series with each winding, but as these only carry normal currents of half the full generator rating, the drop in these reactors is only 5 per cent at full load. In calculating the fault current, the slot reactances of the two windings were reduced to the equivalent value of reactance as obtained from the saturation curves of the generators

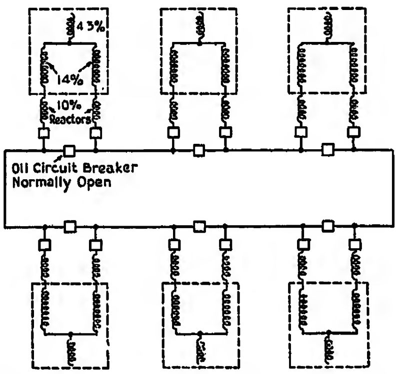

FIG. 16—NEW RING BUS SYSTEM WITH DOUBLE-WINDING GENERATORS. CASE III

with the corresponding current which would flow, in accordance with the discussion in Part III of the paper, but the favorable effect of reduced saturation of the subtransient reactance of the rotor due to the lessened fault currents of the double winding generator was not taken into account.

The slot reactance of the generators next to the fault in Case III was reduced to 57 per cent of its original value for the first instant of fault and for the sustained conditions a saturation factor of 70 per cent was used.

In Case III-A, generators with split belt windings, the slot leakage reactance was reduced to 85 per cent of the original unsaturated value for the instantaneous fault conditions and to 90 per cent for the sustained fault conditions on the generators next to the fault. Saturation did not affect the remainder of the units as the fault current was of such a small magnitude that the units did not saturate.

The obvious disadvantage of this system is the limitation of the kv-a. transfer along the bus. However, as the current in the two windings of a fully loaded generator can safely be divided in the ratio 45:55, there is actually 30,000 kv-a., or 20 per cent, extra capacity available on each bus section, so long as the adjacent bus sections are not overloaded. With the generators operating at their most efficient load, about 75 per cent of rating, either winding can be loaded to 60 per cent of the full generator capacity. Thus, the available transfer power is still considerable, and is fully comparable with that of Case II, when 4000-ampere breakers are used.

The equipment required for this system is much less expensive than for the first two systems, even when they are limited to 4000-ampere breakers and their kv-a. transfer capacity is correspondingly reduced. As compared with Case I only six breakers and two reactors of 4000-ampere capacity are required per generator for a double bus system, instead of 10 breakers and 4 reactors of the same size. As compared with Case II, the same number of breakers and reactors of the same current carrying capacity are required, but the interrupting duty on each breaker is much less for this third case than for either of the first two cases. In the cases which have been calculated, the breaker duty is reduced to about half that required for Case I, or three-quarters of that for Case II. This means that in many cases a double winding generator of the largest size can be installed in an old station, without changing the switching equipment, whereas the use of a single winding generator of equivalent size would require the complete rebuilding of the system and the installation of larger breakers.

Besides this advantage of reduced cost of equipment, this double winding generator system results in greatly increased system reliability. For, even though the voltage on a faulted bus falls to zero during a three-phase short circuit, the connected generators remain in step with the rest of the system, since there is sufficient synchronizing power between the other windings of the generator directly affected, and the rest of the system, to maintain synchronism. This has been verified by factory tests, taken on two small model double winding generators without reactors, which correspond to a more severe condition than normal. Under the same fault conditions for Case I, the generator on the faulted bus section goes out of synchronism, and the adjacent bus section voltages fall to such low values that much

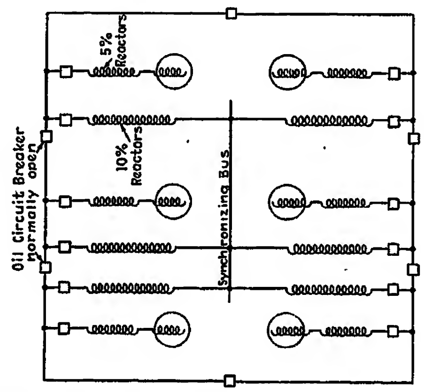

FIG. 17—STAR BUS SYSTEM WITH STANDARD GENERATORS. CASE IV

load is dropped, and the whole system is seriously affected.

The voltages maintained on the bus section near the fault are much higher in this case than for either of the first two cases. Comparing Cases III, III-A, and I, the adjacent bus sections have, respectively, instantaneous voltages of 89, 92, and 51, and the third section from the fault has 99.5 instead of 80 per cent instan-

taneous voltage. The sustained voltages, which are not reached if the breakers open properly, are equally in favor of the double winding generator system. Thus, this system effectively limits fault disturbances to one bus section.

Cases IV and V. At first sight, there does not appear to be much advantage of the double winding generator (Fig. 18) over the standard generator (Fig. 17), when applied to a star bus system, since the numbers and continuous ratings of breakers and reactors required are nearly the same in the two cases. However, the table shows that the interrupting duty of the breakers in Case V is about one-third less than in Case IV, which results in a material saving.

Also, the system stability is greater in the former case, as higher bus voltages are maintained, under fault conditions. In either case, a fault on the synchronizing bus would cause the system to fall apart, so that there is no choice between them in this respect. When one unit is taken out of service, the necessary rearrangement

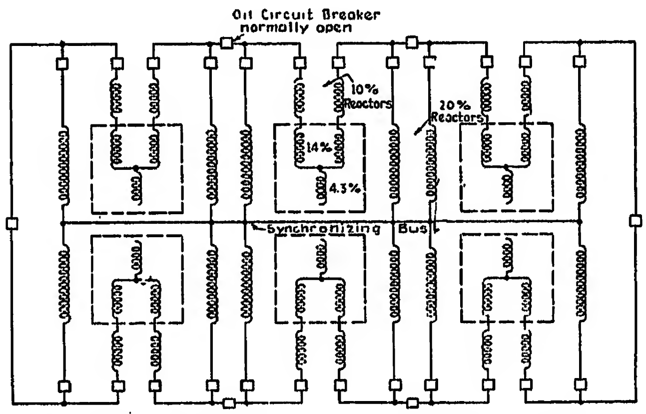

FIG. 18—STAR BUS SYSTEM WITH DOUBLE-WINDING GENERATORS. CASE V

of the system will lead to a much larger concentration of power, and hence greater fault currents, in the single than in the double winding generator case.

The United Electric Light and Power Company has recently advocated and adopted a star bus system with synchronizing at the load as described in an A. I. E. E. symposium on the subject.[4] Either single or double winding generators can be used in this system, but the advantages of the latter are as pronounced in this case as in the comparison of ring bus systems. It will not be necessary to discuss this aspect of the subject here, because the matter was fully presented by Mr. E. E. Chilberg in his discussion of the papers of the symposium just mentioned.

VII. CONCLUSIONS AND ACKNOWLEDGMENTS

Consideration of the data presented in the paper leads to these conclusions.

1. The double winding generator can conveniently be applied in large power stations, using any of the usual systems of bus conections, with resulting large advantages in reduced cost of equipment, lower fault currents, and more effective isolation of faults.

2. The best type of double winding for ordinary purposes is the split belt design, shown in Fig. 3. When ample generator reactor capacity is installed, however, the alternate slot type of winding may be preferable, due to its slightly lower stray losses, and less end winding magnetic forces with unequal loadings.

3. The principal limitations of the double winding generator, due to its low capacity for transfer of power along the bus, and the saturation of its "through" reactance, when excessive currents are transferred under fault conditions, are not usually of great importance. The former may generally be overcome by means of a balancing transformer, and the latter by the use of a reasonable amount of generator reactor capacity.

4. It is, therefore, probable that the double winding generator will become the standard for future power stations, where units of very large size (over 100,000 kv-a.) are installed.

ACKNOWLEDGMENT

The authors acknowledge the material assistance rendered them by Mr. T. F. Barton, whose original thought led to the developments described, Messrs. R. H. Park and D. H. Harms, who contributed many helpful suggestions, and Mr. A. H. Wing, who managed most of the tests.

Appendix A

CALCULATION OF SATURATION FACTORS FOR SLOT REACTANCE

Considering the case of equal and opposite currents in the two circuits of an alternate slot winding:

Let the total r. m. s. current per slot be I amperes, and the slot and tooth dimensions in inches be as shown in Fig. 6. Then, the maximum leakage flux crossing the slot due to the upper coil side, per inch of axial length, is:

$$\phi_1 = \frac{3.19\, I\, \sqrt{2}}{2\, W}\left(d_3 + \frac{d_1 - d_2}{4}\right) \text{ lines,} \qquad (1)$$

and that due to the lower coil side is:

$$\phi_2 = \frac{3.19\, I\, \sqrt{2}}{2\, W}\left(d_3 + \frac{3\,(d_1 - d_2)}{4} + d_2)\right) \text{ lines.} \qquad (2)$$

Their sum is:

$$\phi = \frac{3.19\, I\, \sqrt{2}}{2\, W}\,(2\, d_3 + d_1) \text{ lines.} \qquad (3)$$

Since the flux passing through the tooth root is twice that crossing the slot, the flux density at the bottom of the tooth is:

$$B = \frac{3.19\, I\, \sqrt{2}\,(2\, d_3 + d_1)}{W\, W_t} \text{ lines per sq. in.} \qquad (4)$$

Normally the width of tooth at the gap is about 1.2 W, the ratio of 2 $d_3 + d_1$ to d is about 1.1, and the ratio of W_t to W is about 1.7, so that (4) may be simply expressed in terms of the normal r. m. s. amperes per inch of periphery, Δ, the ratio of actual to normal circuit current, K, and the ratio, d/W, of slot depth to width, by:

$$B = 7.0\, K\, \Delta\, \frac{d}{W}, \text{ approximately, lines per sq. in.} \quad (5)$$

For large turbine generators of normal design, Δ is about 1600 amperes per inch of periphery, and $\frac{d}{W}$ about 7.

As saturation will begin when B exceeds 100,000 Equation (5) indicates that the incidence of saturation in large turbine generators will normally be at about 1.2 times normal circuit current transferred. The actual circuit currents required on the St. Louis and New York Edison double winding generators to produce a maximum density of 100,000 lines per sq. in. at the tooth roots in the center of the phase belt are 1.51 and 1.16 times normal, respectively.

Since the current loading, Δ, was only 780 for the test motor of Fig. 7, it required 3.0 times normal circuit current to produce 100,000 lines per sq. in. maximum density. The calculated through reactance, without saturation, for the motor was only 0.91 of its test value, of which 0.84 was slot and 0.07 zigzag reactance. The extra amount was probably due to end leakage not mutual to the two windings, as it only corresponds to about 0.2 of the total end leakage.

When saturation occurs with increasing current, the through reactance does not diminish toward zero, but approaches a new limit corresponding approximately to the leakage when the teeth are cut off at the roots and the core is removed. In this limiting case, the leakage paths are symmetrical at the top and bottom, as shown in Fig. 8, so that the through slot reactance is reduced approximately as the ratio

$$\frac{2\left(\frac{d_3}{4} + \frac{d_1}{24}\right)}{d_3 + \frac{d_1}{3}} = 0.35, \text{ approximately.} \quad (6)$$

Taking the excess of test above calculated through reactance as non-saturating, due to its air paths, the calculated limiting value of reactance for this particular case is (0.304) (0.91) + 0.09 = 0.37 of its initial value, a value which agrees fairly well with the indicated limit of the test curve. At extreme value of current, the teeth would saturate still further, and the reactance would approach the limit of a complete air path, about ⅓ of this first limit, but such a final limit is probably of no practical interest.

These results indicate that it is necessary to determine rather carefully the saturation factor to be applied to the calculated through reactance of a large generator, so that the amount of reactance actually available for current limitation may be found. It would not be sufficient without examination to use the curve of Fig. 7 for a large machine, since the ratio of lengths of flux path in iron and in air will vary with the size of machine. Before attempting to predict the effective reactances of a large generator, a reactance curve will be calculated to match the test curve of Fig. 7. The method employed in this calculation involves the following assumptions:

1. The effect of saturation is considered to be the inter-position of a series reluctance in the path of the total slot leakage flux, without altering in any way the relative distribution of flux across the slot depth. Actually, the concentration of the iron reluctance at the tooth root will decrease the relatively ineffective portions of the flux crossing the lower part of the slot more than the rest, so that the assumption makes the calculated effect of saturation greater than the true effect.

2. The total ampere turns consumed in the iron corresponding to the m. m. f. of one slot are taken equal to those for the full tooth root density existing over the length of one tooth. Actually, the flux traverses two teeth with varying density, but calculations indicate that the integrated ampere turns over the whole path are about equal to those given by this assumption.

3. The saturation factor for the actual alternating current is taken to be the same as that for a direct current equal to the maximum a-c. value. Actually, the change of wave shape due to reactance will make the effective saturation correspond to a somewhat lower direct current, so that this assumption should make the calculated saturation effect greater than its true value.

4. The effect of the winding pitch will be neglected, calculations being made only for the center teeth of the phase belts, which have the highest flux densities. This also makes the calculated saturation effect greater than the true amount.

5. The saturation factor is assumed to apply only to the excess of the calculated reactance above its limiting value given by Equation (6). The calculated reactance for the test motor is thus determined to be (0.28 + 0.63 K_s) times its unsaturated test value, where K_s is the saturation factor, less than unity.

On this basis, the effect of saturation is to increase the reluctance R, of the slot leakage flux path for a maximum a-c. flux density, B, from the value given by Equation (3):

$$R = \frac{2\,W}{3.19\,(2\,d_3 + d_1)} \quad (7)$$

to

$$R = \frac{2\,W}{3.19\,(2\,d_3 + d_1)} + \frac{2\,(d_1 + d_3)\,F}{B\,W_t} \quad (8)$$

where F represents the magnetizing ampere turns per inch of tooth for a d-c. flux density of B lines per sq. in.

The reactance reduction factor is there given by the ratio of (7) to (8), or is

$$K_s = \frac{1}{1 + \dfrac{3.19\,(d_3 + d_1)\,(2\,d_3 + d_1)\,F}{W\,W_t\,B}} \tag{9}$$

For the particular case of the test motor this becomes:

$$K_s = \frac{1}{1 + \dfrac{70\,F}{B}} \tag{10}$$

The ratio of the reactance determined from (10) by the method outlined under assumption (5) to the unsaturated test value is shown by curve c on Fig. 7. The tests indicate somewhat greater saturation than expected, but they also show an excess of the unsaturated test above the calculated value of reactance, so that good agreement is obtained over most of the range.

A further point to check in this connection is the saturation of the generator subtransient reactance when a short circuit occurs on one winding only. In this case, the flux density at the tooth roots for the same circuit current is only half what it is when the two windings carry equal and opposite currents, since the flux crossing each slot now has the full area of one tooth available. On this account, the saturation curve for the slot leakage reactance of a single circuit should be similar to that of Fig. 7 for the through slot reactance, except for a doubling of the horizontal scale.

However, the limiting value approached by the slot reactance of one circuit as saturation increases is about 0.63 times its unsaturated value, instead of only 0.35 as in the other case. This follows because the reluctance of the path across an empty slot, which the leakage flux takes when the tooth roots are saturated, is represented by

$$\frac{W}{3.19\,(d_1 + d_3)} \tag{11}$$

whereas the reluctance of the path across a slot carrying current is from (7):

$$\frac{2\,W}{3.19\,(2\,d_s + d_1)} \tag{12}$$

The reciprocal of the sum of (11) and (12) is approximately 0.63 times the reciprocal of (12) above, for normal slot proportions. This indicates that the saturation factor given by (10) should be applied to only 37 per cent of the single winding slot reactance.

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Discussion

C. M. Laffoon: There are several points in connection with these different types of double windings which should be given further consideration. In connection with the first, or alternate-slot type of winding, it is gratifying to see that the authors now recognize the fact that the through reactance coefficient is materially reduced by saturation under faulty conditions. This effect of saturation was discovered by L. A. Kilgore last January, and its effect on the through reactance was discussed in a paper presented by the writer at the April, 1929, meeting of the Empire Gas and Electric Association at Buffalo. This question was discussed again by the writer in a paper presented before the meeting of the Association of the Edison Electric Illuminating Companies at Philadelphia on May 17, 1929. These effects were again discussed in an article on "Developments in Generators and Systems as They Affect System Stability," by Messrs. Kilgore and Powers, *Electric Jl.*, October 1929.

In the case of the split-phase type of winding in which the two windings are in alternate groups of slots, there is no general disagreement with the conclusions given in the paper from a qualitative standpoint. The advantages of *this type* of double winding were also mentioned by the writer in the above mentioned paper, which was presented at the meeting of the Association of Edison Electric Illuminating Companies in May, 1929. A turbine generator having a double winding of this type was built in 1915 by the company with which the writer is connected. This machine, which was rated at 3200 kv-a., 178 volts, 6-phase, 60-cycle, 2-pole, 3600-rev. per min., had two independent windings, and each independent winding supplied power to a separate rotary converter. The windings of each pole were arranged in six groups and connected to give two independent circuits. The voltages of the two windings were necessarily out of phase, due to the fact that it was a two-pole machine and each winding was required to be in two parallels on account of the voltage magnitude. However, it was well known at that time that the voltage could have been brought in phase if the voltage had been such as to require the series connection, instead of the parallel connection.

In the case of the third type of winding in which the phase groups of alternate poles are connected in series, it is necessary to use a coil throw of approximately 2/3 to 5/6 pitch, in order to obtain high through reactance. With one winding only, in operation, the estimated values of the 2nd and 4th order harmonics in the stator demagnetizing m. m. f. are relatively large and indicate high additional losses when operating under unbalanced load conditions. The authors have eliminated this type of winding on the basis of excessive losses under unbalanced loads and high stresses on the end turns under short-circuit conditions. The writer does not feel that this conclusion is justified from the actual test results which have been obtained on a 7500 kv-a., 6600-volt, 2-pole, 60-cycle, 3600-rev. per min. generator. This generator was provided with two windings of this type, and the

coil throw was 62.5 per cent. The following tests were made on this machine.

(a) Temperature tests when carrying different values of unbalanced loads.

(b) Locked saturation tests.

(c) Losses under sustained short-circuit conditions.

(d) Instantaneous short-circuit tests.

In obtaining the thermal performance of the machine when operating under unbalanced load conditions, a series of temperature tests was made with 50 per cent of the machine's rated load on one winding and 50, 37.5, 25, 12½, and 0 per cent loads respectively on the other winding. The results from these tests are shown in Fig. 1. In no case does the temperature of either the field or armature windings exceed that reached when operating at full rating, with equal loads on both windings. Another test run was made with 60 per cent of the machine's rated load on one winding and 40 per cent on the other. In this case, the field temperature rise was 8 deg. cent. higher, and the stator temperature rise 15 deg. cent. higher than when carrying full rating with balanced loads. If the load division were 55 and 45

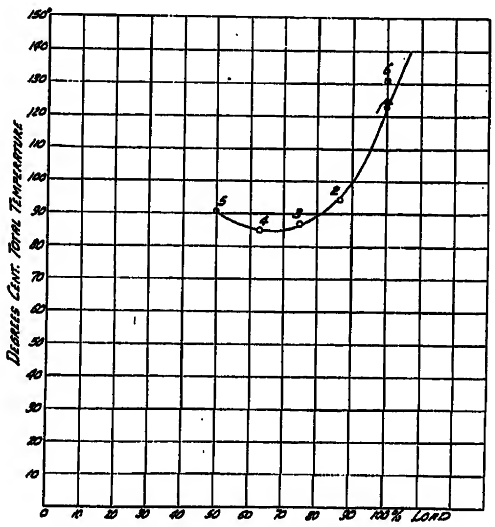


FIG. 1—TEMPERATURE TESTS WITH UNBALANCED ZERO POWER-FACTOR LOADS ON DOUBLE WINDING GENERATOR WITH ALTERNATE POLES IN SERIES

1. 50 per cent load on A winding—50 per cent on B winding
2. 50 per cent load on A winding—37.5 per cent on B winding
3. 50 per cent load on A winding—25 per cent on B winding
4. 50 per cent load on A winding—12.5 per cent on B winding
5. 50 per cent load on A winding—0.0 per cent on B winding
6. 60 per cent load winding—40 per cent on B winding

per cent respectively, it is estimated from these test results that the increase in the temperature rise for both the stator and rotor would not exceed 5 deg. cent. It is also estimated that this machine should deliver 60 per cent of its rating with one winding only in operation, and not exceed the guaranteed temperature on the rotor and no higher temperature rise than with any other type of winding for the stator.

It is agreed that the stresses on the end turns are greater with this type of winding under single-winding short-circuit conditions, because the width of the phase group is greater. However, when the short-circuit tests were made on the 7500-kv-a. machine at full voltage, no observable distortion occurred in the end windings, and it is not anticipated that any unsurmountable difficulties would be encountered in bracing the end turns of windings of this type. Fig. 2 shows the currents delivered by this machine under short-circuit conditions. The curve indicated by A is for the machine with both windings in parallel; the curve indicated by B is for one winding only; and the curve indicated by C is for a short circuit on one winding and the power maintained on the other winding. The currents are expressed in terms of symmetrical r. m. s. values.

These test curves show that there is low coupling between the windings under transient conditions, and there is a high through reactance not appreciably affected by saturation.

The through reactance coefficients obtained from locked tests checked very closely with the calculated values under unsaturated and saturated conditions, and confirmed the results obtained from instantaneous short-circuit tests.

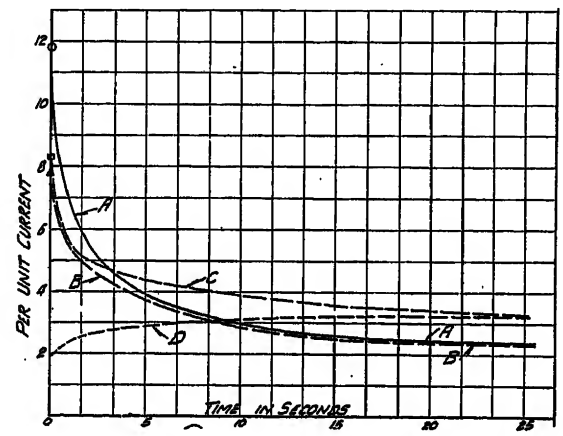


FIG. 2—SUDDEN SHORT CIRCUIT TEST ON 7500-KV-A. 3600-REV. PER MIN.; DOUBLE WINDING GENERATOR. ALTERNATE POLES IN SERIES

A. Both windings in parallel
B. One winding only
C. One winding short circuited and power maintained on the other
D. Winding connected to power supply

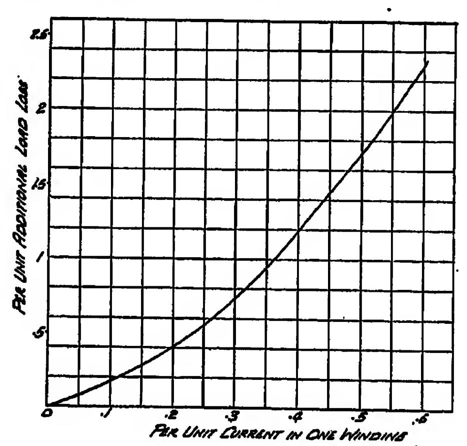


FIG. 3—SUSTAINED SHORT CIRCUIT LOSSES

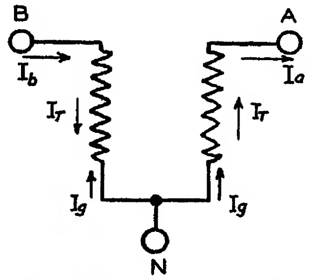
On 7500-kv-a., 3600-rev. per min., double winding generator. Alternate pole in series

The additional losses when operating under sustained short-circuit conditions with one winding only are shown in Fig. 3. It is true that the additional losses are relatively high for large loads on one winding only, but with the machine operating with a maximum allowable unbalanced load of approximately 10 per cent, the additional load losses would not be excessive. In view of the fact that an appreciable part of the additional losses occurs in the end zones, it is felt that they are susceptible to reduction by using different kinds of material in the construction of these parts. In order to evaluate properly the importance of the additional losses, it is necessary to treat each generating station and system on the basis of its own load characteristics and possible unbalanced loads on individual generator windings.

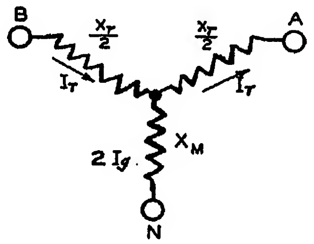
The general conclusions based on analytical and test results indicate that the alternate-pole type of double winding is a very satisfactory winding and should be given consideration for application in which double winding generators are required.

The authors of the paper conclude that the alternate-slot and split-phase types of windings are the only practical windings for commercial applications. My conclusion is that the split-phase, or alternate groups of slots, and the alternate-pole type of double windings are the most desirable types of double windings for commercial applications.

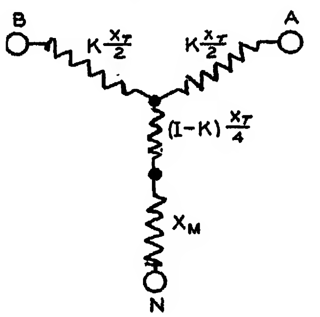
L. A. Kilgore: In this paper the authors have made an extensive study of the effects of saturation in double-winding generators. Before commenting on the authors' analysis the writer would like to present briefly what is believed to be a more accurate analysis.



Single-Phase Diagram of Double Winding Generator Showing Assumed Directions of Currents and Components of Currents



Equivalent Circuit of Double Winding Generator—Unsaturated



Equivalent Circuit of Double Winding Generator Showing Effects of Saturation

Fig. 4

Under fault conditions the currents in the two windings are in opposite directions. It is very convenient to divide the actual currents into two components, one flowing through the machine and the other out of the machine. The through component of current will be equal and opposite in the two windings and the other component currents will be equal and in the same direction in the two windings. Defined in this manner the through component is the average of the two winding currents assumed to be flowing in opposite directions, and the other component is half the difference.

The reactance to the flow of through current is reduced by saturation because the currents flow in opposite directions in adjacent slots or groups of slots, thus magnetizing the teeth radially. The reactance to the other component of current is practically unaffected by saturation, since the currents flow as in a normal single winding machine.

The effects of saturation may be taken into account in short-circuit calculations by changing the equivalent circuit as shown in Fig. 4 herewith. As the authors have stated the effect is to reduce the through reactance by a factor K. However, the authors have not mentioned another effect which can not be neglected. Saturation increases the mutual reactance due to the reluctance of the saturated tooth in the path of the leakage flux; and for complete saturation the reactance is nearly all mutual. This may be accounted for by adding $\frac{1-K}{4}$ times the through reactance to the common leg.

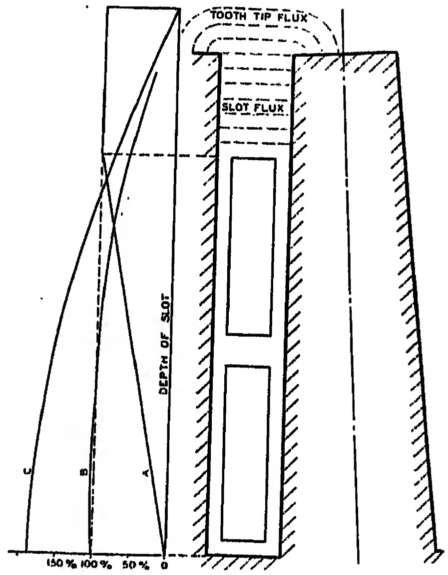


Fig. 5—Slot and Tooth Diagram Showing Radial Densities of Slot Flux in Tooth

A. Density of flux crossing slot
B. Density of slot flux giving radial in the tooth
C. Slot flux in tooth section

The saturation factor K may be calculated from the machine constants and the saturation curve of the stator iron. For short-circuit calculations it is convenient to plot K as a function of through current, which we have defined as the average of the currents flowing in opposite directions in the two windings.

Calculation of Saturation Factor. The method used in calculating the saturation factor K was similar to that given in the paper, except that other appreciable factors such as air paths in parallel with the iron, and wave distortion were taken into account.

However, the writer disagrees on one significant factor. The authors have considered a limiting value of reactance about 0.35 the unsaturated value, and have applied the saturation factor K_s to the remaining 0.65. This limiting value was based on the assumption that the effect of saturation is as if the teeth are cut off at the roots and the core removed. The authors then calculated the limiting value considering only the reluctance of the slot, and assuming infinite permeability for the tooth itself.

Fig. 5 shows the actual flux going radially in the tooth of a large 4-pole double-winding machine. It will be seen that the tooth taper offsets the increase in flux going radially so that the densities are nearly uniform through the bottom half of the

tooth. For the case worked out the average density for bottom half is 98.5 per cent of that at the base when saturation begins. For higher currents the density at the center would undoubtedly be higher than at the base.

It is apparent then that for 2- or 4-pole machines at least there is no limiting value of reactance determined by cutting-off the teeth at the base. The real limiting value can be approximated by assuming the effect equivalent to cutting out the bottom half of the tooth. This would give a limiting value about 0.035 instead of 0.35.

The curves of Fig. 6 show saturation factors for a 150,000-kv-a., 4-pole turbine generator connected in the several ways which have been described. The values for the alternate-slot type were calculated as has been outlined above. The points marked with a circle are test points from sudden short circuit on a model generator with an alternate-slot type of double winding. These tests indicate definitely that the degree of saturation is about that calculated, and that there is no apparent limiting value of about 0.35.

Alternate Groups of Slots. A curve of saturation factors for alternate pairs of slots may be constructed from the curve for alternate slots on the same machine. Saturation begins at the same current, but for a given density half the ampere turns per slot are required for the iron, since each slot now furnishes magnetizing ampere turns for only one tooth instead of two.

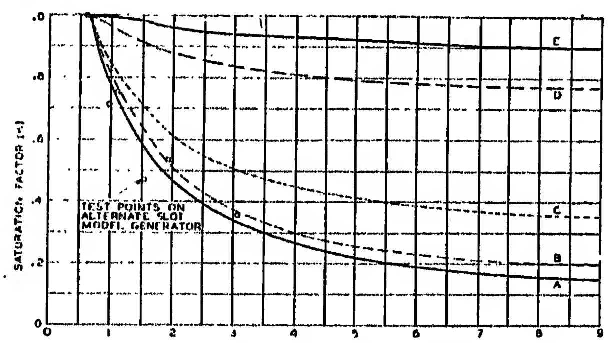


FIG. 6—SATURATION FACTORS FOR 150,000-KV-A. DOUBLE WINDING GENERATOR. FOUR POLES—60 SLOTS

Versus through current for:
A. Alternate slots
B. Alternate pairs of slots
C. Alternate groups of 2 and 3
D. Alternate poles
E. *K vs.* total generator current for single winding machine

The through current times K, ($I_T K$), is proportional to the slot flux and consequently tooth density; and $(1 - K) I_T$ is proportional to magnetizing ampere-turns for the teeth. Then for the same densities

$$K' I_T' = K I_T$$

or

$$I_T' = \frac{K I_T}{K'}$$

$$(1 - K') I_T' = \frac{(1 - K)}{2} I_T$$

or

$$K' = \frac{2K}{1 + K}$$

For alternate groups of slots (more than two) only the end slots of a group supply magnetizing ampere turns to the teeth between the groups. The ampere-turns available across the middle slots are greater than the end slots by the amount of the magnetizing ampere-turns required for the iron. This causes an increased interlinkage with the middle slots. A saturation-factor curve may be constructed from the curve for alternate slots in the same way as for alternate pairs of slots but taking into account the increased interlinkage with the middle slots. Since only the flux of the end slots is affected appreciably by saturation, a portion of the reactance is unaffected. The slots per group less two is a measure of the part unaffected. It may readily be seen that with three or more slots per group considerable improvement in saturation factor can be obtained.

Taking half the conductors of a phase belt as one group gives the winding which the authors have termed the split-phase belt winding. Using each phase belt as a group of conductors gives the maximum slots per group a minimum saturation effect. This type has been termed alternate poles in series.

In order to compare the several types of windings consider the values of K from the curve of the 150,000-kv-a. machine with a through current of 2.5 times rated current.

Type of winding	Value of K for $I_T = 2.5$
Alternate-slot winding	0.40
Alternate pairs of slots	0.43
Alternate groups of 2 and 3 slots	0.54
Alternate poles in series	0.85

The above saturation factors might be compared with that for a single-winding machine on a similar system by taking the value at 4 times rated current for the machine. The curve shows a value of 0.96 for a winding pitch of exactly 2/3; however, at any other fractional pitch this factor would be nearer unity.

From this comparison it is evident that a large reduction of through reactance can be expected on an alternate-slot winding with 15 slots per pole. It might be well to note that saturation effects occur at lower current values for machines with a larger number of slots per pole. Alternate pairs of slots show little improvement. Alternate groups of slots show considerable gain. Alternate poles in series show relatively little reduction in reactance.

Alternate Poles in Series. The through reactance of the alternate-pole type is affected much less by saturation than the other types. Furthermore, this winding has a self-inductive belt leakage and only part of the end-winding leakage is mutual. These factors give a higher through reactance than can be obtained with the other windings. Consequently this type of winding with the same external reactance would give least short-circuit current and system disturbance, or on the basis of the same current would require a minimum amount of generator reactors or none at all.

The authors consider this type distinctly undesirable because of additional load loss with unbalanced loads. Mr. Laffoon has shown actual tests on a machine of this type. It is possible that these losses can be reduced. The choice between alternate poles with some additional loss or the split-phase belt winding with the necessary additional reactors depends upon the average amount of unbalance for a given application.

R. E. Powers: The outstanding purpose of providing alternators with double windings is to secure a combination of generators, supplying a given load, that will have low reactance to the normal flow of power current, but will have high reactance to the flow of fault current. The double-winding generators so far considered have been affected by the saturation of the slot leakage reactance path, due to the flow of through current, and consequently their effectiveness has been reduced.

To minimize the detrimental action of saturation within the unit itself, and to provide the necessary limiting reactance, heavy generator reactors have been utilized in the individual generators leads. The addition of generator reactors inherently reduces the fault current that can flow, consequently minimizing the saturation of the unit, the combination of generator reactors and alternator inherent reactance being sufficient to reduce the short-circuit currents to the required value.

The ideal type of double-winding generator, from a short-

circuit standpoint, is one in which the "through" reactance is high and in which saturation of the leakage path is not present to any marked degree, making the use of external reactors unnecessary, the inherent reactance of the unit alone limiting the current to the required value.

Mr. Kilgore has shown that the effects of saturation are considerably less in a double-winding generator designed so as to secure the individual windings by connecting alternate poles in series than in any of the other types so far considered at the value of through currents encountered in actual practise. The saturation factor for a given 150,000-kv-a. double-winding alternator with the winding arranged in alternate slots is 0.39, whereas with the windings arranged on alternate poles the saturation factor was increased to 0.85 when carrying 2.5 per unit through current.

The comparison of saturation factors for the two windings was made on the basis that the same stator frame was used and that new windings, the best suitable for each type, were used. It might be pointed out that some variation in the ratio between saturation factors may be expected as the generator design proportions are changed.

Fig. 7 herewith shows a comparison of results secured from short-circuit studies on various types of double-winding generators when connected in a ring bus, or synchronized through the load network. The double-winding alternate-pole generator has an unsaturated through sub-transient reactance of 53.2 per cent, and an over-all sub-transient reactance of 15 per cent. The alternate slot and groups of slots type unit had a subtransient through reactance of 50 per cent and an over-all subtransient reactance of 15 per cent.

The comparison of the performance of double-winding units of various types, when connected in a ring bus, was made on the basis that equal initial currents were to be secured. Saturation of each unit was taken into consideration and faults were taken from full load. In order to secure equal initial currents, external reactors of 9.6 and 6.2 per cent respectively must be added in series with the alternate-slot and grouped-slot double-winding generators, and 15 per cent to the standard generators, in order to equal the performance of the unit with alternate poles in series. The instantaneous symmetrical current was limited to 55,000 amperes. However, it will be noticed that the sustained value of short-circuit current varies from 24,700 amperes to 29,000 amperes, depending upon the type of unit used. The combination using alternate poles in series to secure the double winding has the highest instantaneous and short-time voltage on all buses. The sustained voltage on the first and second bus is also highest for the alternate-pole type. However, the sustained voltage on the third bus is highest for the unit that has the lowest saturation factor. The unit with the lowest saturation factor requires the greatest values of external reactance and consequently the circuits which are unaffected by saturation have a greater total reactance, resulting in a different distribution of currents and voltages.

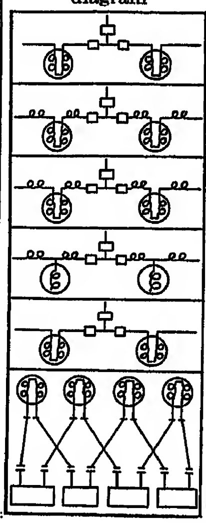
The results of analysis on standard units using combination generator and bus reactors, are shown on line 4.

In all of the analyses shown on line 1—5, back feed was not taken into consideration.

In the last two sections of the chart are shown the results of analyses made on a system using alternate-pole double-winding units synchronized through the load network. In case I the reactance between the internal voltage of the unit under consideration and internal voltage of all other units in parallel was set at 60 per cent; case II at 40 per cent.

Fig. 7

THREE-PHASE FAULT ON BUS SECTION. SHORT CIRCUIT VALUES BASED ON 7–150,000-KV-A., 13,800-VOLT GENERATORS SHORT CIRCUITS APPLIED UNDER FULL LOAD CONDITIONS

System and constants	Single line diagram	Short circuit currents and kv-a.: Inst. symmetrical	One-tenth second	Sustained value	Fault	Voltage on adjacent busses: First bus 0	First bus 0.1	First bus Sus.	Second bus 0	Second bus 0.1	Second bus Sus.	Third bus 0	Third bus 0.1	Third bus Sus.
Double-winding generators.. Alternate poles in series..... No reactors................		55,000 A. 1,310,000 Kv-a.	43,000 A. 1,030,000 Kv-a.	24,700 A. 590,000 Kv-a.	0	91.4	80	50	99	96.5	84	100	100	93.3
Double-winding generators.. Alternate groups of slots.... 6.2 per cent reactors........		55,000 A. 1,310,000 Kv-a.	41,600 A. 995,000 Kv-a.	25,000 A. 597,000 Kv-a.	0	86	75	57	98.5	96.5	81	100	100	94.7
Double-winding generators.. Alternate slots............. 9.25 per cent reactors.......		55,000 A. 1,310,000 Kv-a.	42,100 A. 1,010,000 Kv-a.	25,600 A. 615,000 Kv-a.	0	82.5	71	53	99	95.5	81.4	100	99.5	95.5
Standard machines......... 15 per cent reactors.........		55,000 A. 1,310,000 Kv-a.	47,600 A. 1,140,000 Kv-a.	29,000 A. 694,000 Kv-a.	0	70	67.3	50.5	92	86	68.5	96.5	92.6	83
Double-winding generators.. Alternate slots............ No reactors................		97,000 A. 2,320,000 Kv-a.			0	54			91.2			100		
Double-winding generators.. Alternate poles in series..... Synchronized at load....... Reactance from internal voltage of one machine to all others in parallel, 40 per cent = Case I 60 per cent = Case II						Faulted gen. bus			Unfaulted gen. bus			All other busses		
		33,400 A. 795,000 Kv-a.	28,400 A. 676,000 Kv-a.	17,400 A. 405,000 Kv-a.	0	0	0	0	91	71	47.5	96	93.5	88
		41,200 A. 981,000 Kv-a.	30,600 A. 871,000 Kv-a.	24,650 A. 585,000 Kv-a.	0	0	0	0	87	66	46	93.7	90	81

In both cases, the instantaneous symmetrical fault current was decreased from the base current of 55,000 amperes used in comparison in items 1—5 to 33,400 amperes and 41,200 amperes respectively. The chart shows sustained values of voltage on all other buses of 88 per cent and 81 per cent, which would appear to be low in comparison with the systems shown in lines 1—5 of the table. In the system synchronized at the load, the system comprises the reactance between units and the results shown on the table take back-feed into consideration and represent the actual values of current and voltage incident to a given fault, whereas back-feed is not taken into consideration in the comparison in lines 1—5; its effect would be to lower the voltage on adjacent buses, the reduction depending upon the amount of external interlacing between the bus sections.

A study of Fig. 7 indicates clearly that the alternate-pole type double-winding generator has considerable advantage from a short-circuit standpoint. Generators of 150,000 kv-a. can be connected into a bus system, either ring bus or synchronized at the load, and standard oil circuit breakers in the class already de-

veloped, can be used without external generator or bus reactors which undoubtedly will result in switch house simplification and a reduction in cost.

The authors have shown that the alternate pole in series type of double winding unit has increased stray losses with unbalance in load current carried by the individual windings. The test results shown by the authors in Fig. 13, and by Mr. Laffoon in a slide are secured by loading one winding only, the other being unloaded. During normal operation, it is not expected that a unit will be run with 60 per cent of the generator output on one winding, and no load on the other. I believe it would be fair to assume that the maximum unbalance between windings would be 20 to 30 per cent with an average unbalance considerably below that figure, on the order of 10 to 15 per cent. Under such operating conditions, the additional stray losses will not be excessive. In units utilizing external generator reactors, the kilowatt loss in the reactors is no small item. The loss in the 9.2 per cent reactor and 6.2 per cent reactor used in the alternate slot and grouped slot units is approximately 70 and 50 kw. respectively. The loss in external generator reactors is of a constant nature, that is, it is present at all times irrespective of unbalance, whereas the increased stray losses are a function of unbalance.

Undoubtedly, the double-winding unit will find its greatest application in metropolitan areas where considerable energy is transmitted at generator voltage. Consequently, numerous feeder positions will be available. With a flexible bus arrangement similar to that used in many stations today, the output of the generator circuits can be fairly well balanced.

With proper interlacing of the feeders in a system using double-winding generators synchronized at the load, the output of each winding will inherently be balanced and additional stray losses will not be a factor.

In a system in which the total output of the station is taken out through a relatively small number of high-capacity feeders, unbalance between generator windings will probably be of a high order, and the alternate-pole type of winding would undoubtedly be unsatisfactory.

The decision as to which type of winding could be used for a given application will depend upon the general system layout, bus arrangement selected, probability of continued unbalance between windings, capitalization of losses, and valuation of space within the switch house.

The curves shown in Fig. 10 of the paper bring out a very important point, and that is that under short-circuit conditions, the double-winding generator delivers less current to the fault with consequent smaller reaction of the armature on the field. Under such conditions, the internal voltage of the generator decays at a much slower rate.

In Fig. 2 of Mr. Laffoon's discussion are shown terminal short circuits on a standard generator and a double-winding generator in which one winding only is shorted, the other winding being connected to an infinite bus. Under such conditions, the net armature demagnetization is a function of the difference of the currents in the two windings and consequently considerably reduced over what it would be in a standard unit when both windings were shorted simultaneously.

The double-winding generator gives in effect the results of a single-winding unit with a very high short-circuit ratio and opens up the possibility of designing large double-winding generators with short-circuit ratios on the order of 0.85 to 0.9, and securing the same rate of decay of internal voltage as is secured in the present designed unit with higher short-circuit ratios.

D. D. Chase: Mr. Powers presents a chart showing the fault conditions where double-winding generators of the three types (alternate-slot, split-phase-belt, and alternate-pole) were used. The generator with the alternate-pole winding had 2/3 pitch, which gives the maximum self inductance between the two windings, and hence the highest possible through reactance, due to the fact that no bars of different windings are ever in the same slot. However, if about 80 per cent pitch is used, as is desirable and usual for large 1800-rev. per min. machines, the two windings will have nearly half their conductors in the same slots, thus cutting the initial through reactance to about 60 per cent of that for the alternate-slot cast. The lower initial reactance in this case, therefore, cancels the gain from reduced saturation, and leaves the alternate-pole winding with the net disadvantage of inferior performance under unequal loading.

When the number of slots per pole is reduced, the three types of winding become more nearly alike in their characteristics, and it is evident that when there is only one slot per pole per phase, the alternate-slot and alternate-pole windings become identical, and the split-belt type becomes impossible. In general, the fewer slots there are per pole, the higher the inherent reactance is, so that the type to be used is a matter of convenience, rather than importance, when there are less than 4 slots per pole per phase. However, we do not agree with Mr. Laffoon's statement that the split-belt type is limited to cases where the pitch is between 2/3 and 5/6.

The question was raised whether it was necessary to have generators which would operate with unbalanced loads. Most turbines are designed so that the most efficient point of operation is near 2/3 load, and it is, therefore, a very common practice to operate at about this load condition. Of course, there are some base-load stations where the turbines are operated at full capacity, because the station is much more efficient than any of the others, and the best over-all efficiency is thereby secured. However, the base-load station of today becomes the peak-load station of tomorrow, and hence it is soon very apt to be operating at reduced loads. If it is possible to design a generator so that one winding can be loaded to 60 per cent of its rating, when the other winding is unloaded, it is very desirable to do so, as it simplifies operation considerably by eliminating the balancing of loads on the various bus sections.

There are many power companies who operate all of their stations at approximately ¾ load, as all have approximately the same efficiency. In this way, the turbines are run at the best operating point, the equipment is not stressed to full capacity, and there is a reserve supply of power in every station to take care of sudden increase of load or loss of other power supply.

In this connection, the recent load division of the 160,000-kw., 25-cycle, double-winding generator is of interest. This unit has been in operation only a short time and has been operated already with a load of 90,000 kw. on one winding and 30,000 kw. on the other. The unit has also been carrying 80,000 kw. load on one winding with no load on the other.

E. H. Freiburghouse: It was not until 1927, when T. F. Barton pointed out their advantages, that the use of double-winding generators for limiting fault currents and maintaining system stability was considered. Just what type of winding should be used for this purpose is largely a matter of judgment. Originally, we did not give the question of saturation of the leakage paths as much consideration as it deserved, believing that the use of adequate reactors and the retention of the best characteristics for unequally loaded operation were desirable. Lately, the tendencies to still further concentrate large amounts of power on each bus and to limit reactor capacity have led us to recommend the split-belt winding in place of the alternate-slot winding, thus securing less saturation at the expense of slightly inferior performance with unequal loading.

We do not recommend the alternate-pole type of winding, for the reasons that it is distinctly inferior to the other types in respect to stray losses, heating, and stresses, when unequally loaded.

We know that the subtransient reactance of a single-winding generator, as well as that of a double-winding machine, varies greatly in inverse relation to the fault current. From a study of the many short-circuit tests we have made upon standard machines we feel quite certain that saturation of the subtransient reactance is much greater in most cases than that indicated by Curve *E*, Fig. 6, of Mr. Kilgore's discussion.

Mr. Kilgore's ideas on the calculation of saturation are sound and well expressed, and it is interesting to see the results he has reached from a somewhat different standpoint. It should be noted that Curve *C* of his Fig. 6, corresponding to alternate groups of 2 and 3 slots per belt, shows considerably less saturation than Curve *B* for alternate pairs, thus confirming the conclusion that for the usual split-belt winding of a large machine with about 4 slots per belt the saturation is about as shown in our Fig. 12.

Another reason for desiring to have a generator which can operate with unbalanced load is shown by the present Cahokia Station layout. When it is advisable to take a bus out of service for cleaning, the other winding of the generator can continue to carry load to its capacity. If the generator could not operate under these conditions, the unit would have to be shut down, as there is no way of transferring the winding from the bus which is to be cleaned to another bus.

A 40,000-Kw. Variable-Ratio
Frequency Converter Installation

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***Synopsis.**—Part I of this paper describes the installation of two 20,000-kw., adjustable load, variable-ratio, frequency converters interconnecting the 25-cycle and the 60-cycle systems of the Niagara, Lockport and Ontario Power Company at Lockport Substation about twenty miles from Niagara Falls and Buffalo, N. Y. It also explains the function of the various machines, points out the more important features of the control, and relates a few interesting incidents in the past eighteen months of operation.*

Part II describes and explains the characteristics of such a converter and, more intimately, the operation and design of the component apparatus, using rather generally known and understood analogies, comparisons, and simple physical conceptions without any mathematical analyses or difficult theoretical treatment.

* * * * *

PART I

THE Niagara, Lockport and Ontario Power Company was organized in 1906 for transmitting and distributing power in the western and central parts of New York State. The power was generated and transmitted at 25 cycles. Some of the larger customers were distributing companies and municipalities having 60-cycle distribution systems, and in some cases 60-cycle generating equipment. As a result of the difference in frequency between the transmitted power and the distribution systems, several installations of frequency converters were made, each with reserve capacity for emergency use.

In addition to several existing synchronous-synchronous frequency converters, it was decided in 1924 to install two 6000-kw. variable ratio converters at the eastern end of the 25-cycle system, making possible interconnections with the 60-cycle systems of the Northern New York Utilities Co. and Adirondack Power Co. and at the same time providing 60-cycle power for the Syracuse Lighting Company whose frequency converters were loaded nearly to capacity.

The two frequency converters were installed at Altmar, N. Y., where a 110-kv. connection was made to the Northern New York Utilities System and a double circuit 110-kv. line was constructed to Syracuse, N. Y. where connections were made to the Syracuse Lighting Co. and the Adirondack Power Co. systems.

In 1925, a third 6000-kw. variable-ratio converter was installed at Jamestown, N. Y., in order to provide a means of interconnecting the 25-cycle system with the 60-cycle system of the Penn Public Service Corporation.

In 1927, in order to consolidate the 60-cycle sections of the system and to supply the additional requirement of 60-cycle power to those customers distributing at this frequency, 60-cycle, 110-kv. circuits were provided connecting the eastern and western ends of the system. At the same time two 20,000-kw. variable-ratio frequency converters were ordered for installation at Lockport, which is about in the center of both the 25- and 60-cycle systems.

The two 20,000-kw. converters have now been in service for about eighteen months, serving as the main interconnection between the 25- and 60-cycle systems.

The 25-cycle power system has an installed generating capacity of about 1,000,000 kv-a., of which the Niagara Falls Power Co., the Buffalo General Electric Co., and the Hydro-Electric Power Commission of Ontario system are parts. The 60-cycle power system has an installed generating capacity of about 600,000 kv-a., of which the Niagara, Lockport and Ontario Power Co., the Northern N. Y. Utilities Co., the Mohawk-Hudson Power Corp., and the New England Power Co. systems are parts.

The load on these 20,000-kw. sets is inherently adjustable independently of the generating stations and can be maintained constant at any desired load regardless of variations in the frequencies of the two interconnected power systems, provided these variations do not exceed the range for which the set has been designed, *i. e.*, from 98 per cent to 101 per cent of the nominal 25:60 frequency ratio.

Within this frequency ratio range, the converters are completely reversible and can transmit their rating of 20,000 kw. in either direction.

The main synchronous machine and the main induction machine of each frequency converter are capable of operating as a synchronous and an asynchronous condenser respectively, at a capacity of 20,000 kv-a. zero power factor (over-excited), but not simultaneously. When operating as a condenser, the induction machine is asynchronously excited through its rotor by the regulating machines.

This part of the paper is intended to describe the equipment as installed and to review some of the outstanding events during its operation. It is believed such a description will be of interest inasmuch as these equipments constitute a major advance in interconnection apparatus from considerations of both type and

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capacity. The design of the equipment is somewhat unique and the capacity of each set is between three and four times greater than that of any previously installed frequency converter of similar type.

Each 20,000-kw. converter consists of the following machines:

MAIN SET (all machines direct and rigidly connected):

One 24-pole synchronous machine, rated 25,000 kv-a., 0.8 power factor (over-excited), 20,000 kw., 12,000 volts, 1200 amperes, three-phase, 60 cycles, 300 rev. per min. without exceeding observable temperature rises of 60 deg. cent. on the stator (armature) and 80 deg. cent. on the rotor (field) as measured by embedded detectors and the change in resistance respectively.

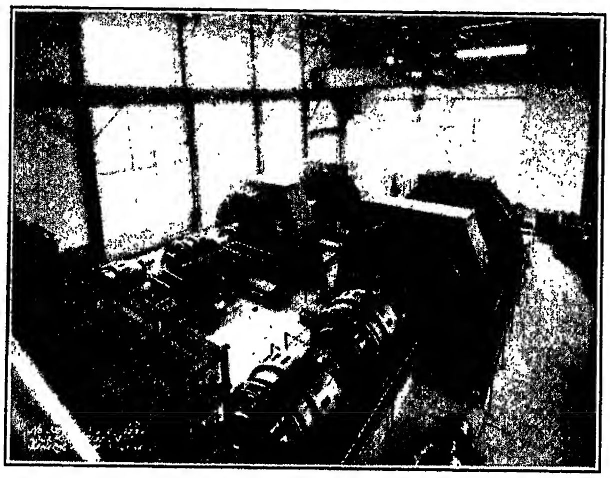

FIG. 1—TWO 20,000-KW. VARIABLE-RATIO FREQUENCY CONVERTERS

The two direct connected units in the foreground are those of the double unit regulating machine. The third machine is the main induction machine and in the background is the main synchronous machine. In the left foreground are the accelerating resistors

One 10-pole wound rotor induction machine, rated 23,000-kv-a., 0.95 power factor (over-excited) 28,000 hp. 12,000 volts, 1110 amperes, three-phase, 25 cycles, 300 rev. per min., without exceeding observable temperature rises of 60 deg. cent. on both stator (primary) and rotor (secondary) as measured by embedded detectors and thermometers respectively.

One overhung shunt wound d-c. generator, for exciting the field of the 25,000 kv-a. synchronous machine, rated 165 kw., 250 volts, 660 amperes, 300 rev. per min.

One double unit three-phase a-c. commutator machine, for exciting the secondary (rotor) of the 23,000 kv-a. induction machine, the two units connected in series and each rated 1925 amperes, three-phase, 375 kv-a., 112.5 volts, 0.5 cycles.

AUXILIARY SYNCHRONOUS EXCITER SET (Machines direct connected):

One synchronous exciter, for exciting the rotor of the 750-kv-a. double unit a-c. commutator machine rated 350 kv-a., 130 volts, 900 amperes, three-phase, (6 leads) 25 cycles, 750 rev. per min.

One synchronous driving motor, rated 80 hp., 1.0 power factor, 440 volts, 87 amperes, three-phase, 25 cycles, 750 rev. per min.

One d-c. generator, for exciting the fields of the synchronous exciter and driving motor of this set, rated 17.5 kw., 115 volts, 150 amperes, 750 rev. per min.

Fig. 1 is a view showing the two adjustable-load, variable-ratio frequency converters as installed. Fig. 2 is an elevation drawing of one of the main sets showing the physical arrangement of the machines and their foundations. Fig. 3 is a diagram indicating the mechanical and electrical interconnection of the apparatus comprising a set. The captions accompanying the individual figures are explanatory.

The stator winding of the 25,000-kv-a. synchronous machine provides the sole connection of the converter set to the nominal 60-cycle power system. Due to the inherent "non-slip" characteristic of synchronous machines, its rotor and therefore the entire rigidly coupled rotating part of the main set operate in exact synchronism with the actual frequency of the nominal 60-cycle system. In other words, the speed of the main set which includes the rotor of the main induction machine is solely determined by the actual frequency of the power system energizing the synchronous machine stator and is independent of the frequency of the power system energizing the induction machine stator.

The stator winding of the 23,000-kv-a. induction machine is connected to the nominal 25-cycle power system and its stator flux rotates in synchronism with the frequency of this power system. The non-synchronous, "shunt" speed-torque characteristics of an induction machine allows "slip" between its stator flux and rotor speed. Consequently this induction machine is the part of the frequency converter that provides the "loose" coupling between the two power systems so as to accommodate the variations in frequency or departures from the nominal 25:60 frequency ratio.

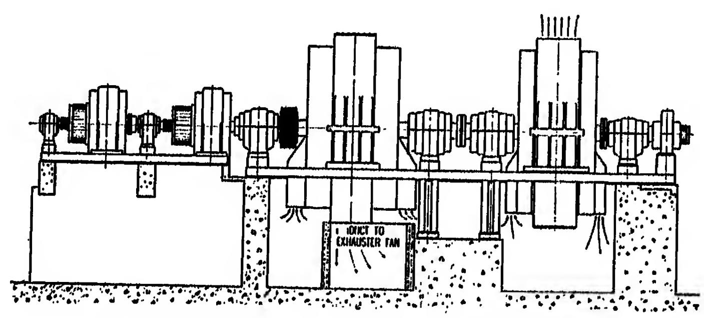

FIG. 2—AN ELEVATION DRAWING OF A MAIN SET

To the left are the two units of the regulating machine, then the main induction machine, the main synchronous machine, and to the right the d-c. exciter for the main synchronous machine

The double unit regulating machine and the auxiliary synchronous exciter set constitute the load adjusting equipment for the converter set. These machines change the speed-torque characteristic of the wound rotor induction machine.

The regulating machine is the means whereby three-phase, alternating voltages at slip frequency and of adjustable magnitude and phase relationship are induced in the rotor circuit of the main induction machine, thereby raising or lowering the "shunt" speed-torque characteristic as desired.

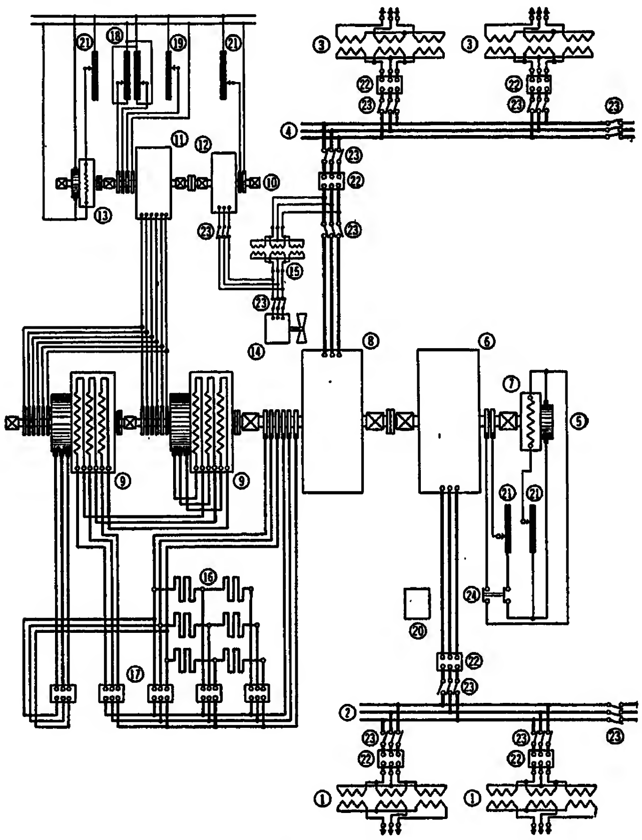

FIG. 3—CONNECTION DIAGRAM OF VARIABLE-RATIO FREQUENCY CONVERTER

A fundamental diagram of the set is shown in Fig. 7

1 Transformer: 12,000-kv-a., 110/12-kv., 60 cycle
2 60-cycle bus.
3 Transformer: 12,000-kv-a., 63.6/12-kv., 25-cycle
4 25 cycle bus
5 Main unit: 300 rev. per min.
6 25,000 kv-a., 60-cycle synchronous machine
7 165-kw., d-c. exciter
8 23,000-kv-a., 25-cycle induction machine
9 375-kv-a., regulating machine unit
10 Auxiliary unit: 750 rev. per min.
11 350-kv-a., 25 cycle synchronous exciter
12 80-hp., 25-cycle synchronous motor
13 17.5-kw., d-c. exciter
14 60-hp., 25-cycle induction motor (exhauster fan)
15 Transformer: 3 × 50-kv-a., 12/0.44-kv., 25-cycle
16 Starting resistors
17 Oil circuit breakers for starting
18 Load rheostat
19 Power factor rheostat
20 Automatic load regulator
21 Field rheostat
22 Oil circuit breaker
23 Disconnect switch
24 Field circuit breaker

The synchronous exciter of the auxiliary set excites both units of the regulating machine and is the medium controlling the voltages induced by them. This synchronous exciter is essentially a three-phase, 25-cycle synchronous generator except that it has two field windings, one controlling the load component of the induced voltage and the other, the power factor component. In the "load field" is a motor operated potentiometer type rheostat providing reversible excitation, and in the "power factor field" is an ordinary motor operated rheostat. By manipulation of the excitation of this synchronous exciter, load and power factor control of the 23,000 kv-a. induction machine is obtained. These two simple and reliable rheostats are the sole controlling devices.

The design of these load adjusting machines will be described in Part II of this paper.

The main set consists of five machines with five rotors rigidly connected together and running at a nominal speed of 300 rev. per min., the actual speed being determined by the actual frequency applied to the stator of the main synchronous machine. This rotating part is supported in six pedestal bearings as indicated in Fig. 2. One structural steel bed-plate supports the frames of the main machines and four pedestal bearings; a separate structural bed-plate supports the frames of the two regulating units and two pedestal bearings. The operation of the set has been completely successful with this mechanical arrangement.

Space and bedplate accommodations have been provided for the axial shift of all machine frames so as to facilitate uncovering the individual rotors in case air-gap repairs should be needed.

Both ends of each of the three separate rotor phases of the main induction machine are brought out to individual collector rings. The locked rotor secondary voltage per phase is 4080 volts and the current at rated load is 1925 amperes per phase.

All machines are self-ventilated except the 23,000-kv-a. induction machine. Because of the small air-gap economically inherent in an induction machine and the lack of any appreciable fan effect of the smooth drum rotor, the ventilation of this machine is provided by a separate turbo-conoidal exhauster fan having a capacity of 84,000 cu. ft. of air per minute at a static pressure of 2½ in. of water. This fan is driven by a 60-hp., 725-rev. per min., squirrel-cage induction motor; is located in a ventilating chamber in the basement connected to the lower discharge chimney of the main induction machine; and discharges the warm air through a screened opening in the station wall.

The regulating machine was built in two units in order to keep the design, particularly that of the commutator, within conservative and reliable limits. Results are more than gratifying. The commutation of these units is black under all conditions. After eighteen months of operation with only normal atten-

tion, the commutators are in excellent condition and the brushes are brightly polished over their entire face. The brush life promises to be two or three years at least.

The 80-hp., 750-rev. per min., synchronous motor driving the auxiliary exciter set and the 60-hp., 4 -pole, squirrel-cage motor driving the exhauster fan are both supplied with 440-volt, three-phase, 25-cycle power through auxiliary step-down transformers, which are connected directly to the stator leads of the main induction machine. Both motors are started at rated voltage simultaneously with the energizing of the induction machine stator.

In starting the converter, the main induction machine is used as a wound rotor induction motor with secondary accelerating resistors in each of the three separate rotor phases. The acceleration is in three steps accomplished automatically under the control of a motor driven drum type relay. Full speed is reached in less than 90 seconds and the maximum inrush is about 10,000 kv-a.

The converter cannot be started unless the two regulating machine units are disconnected from the rotor circuit of the large induction machine; the second and third accelerating breakers are open; the two rheostats controlling the excitation of the synchronous exciter are in the minimum excitation position; and the motor driven accelerating relay is in the starting position. These things being all correct, starting of the converter is initiated by merely turning one control switch. This closes the first accelerating breaker, which is automatically followed by the closing of the main breaker in the primary leads of the main induction machine, and the starting of the motor driven accelerating relay. The ventilating fan and the auxiliary exciter set are brought up to speed at the same time that the main induction machine stator is energized. After a period of about 35 seconds, the motor driven relay closes the second accelerating breaker and 30 seconds later the third accelerating breaker which short circuits the rotor of the main induction machine. About 20 seconds later, by which time the main set is completely accelerated, the motor driven relay closes the two breakers connecting the regulating machine units to the rotor circuit of the main induction machine provided the auxiliary exciter set is up to synchronous speed. As soon as both breakers connecting the regulating machine to the rotor of the main induction machine have closed, the three accelerating breakers open, leaving the collector rings of the induction machine connected to the regulating machine units only. This entire sequence is automatically and positively provided and fully insured by interlocking.

After the foregoing has been accomplished the main synchronous machine may be manually synchronized with the nominal 60-cycle bus and connected to it. Synchronizing is done in the normal way, the speed of the converter being adjusted by manipulation of the load rheostat. This affects the speed for synchronizing just as does manipulation of the governor of a prime mover and is equally simple. After the converter is connected to both power systems, manipulation of the load rheostat continues to have the same effect as manipulation of the governor of a prime mover driving an alternator, both tending to force or retard the rotor speed and resulting in a change in kilowatt load, the speed being restrained by the synchronous machine.

An automatic load regulator of the rheostat controlling type is provided as a part of the control gear. This regulator governs the load rheostat to maintain any desired transfer of power in either direction independently of variations in the frequency of either of the interconnected power systems.

The manually adjusted power factor rheostat controls the excitation of the main induction machine, its effect being very similar to the corresponding field and reactive volt-ampere adjustment of a synchronous

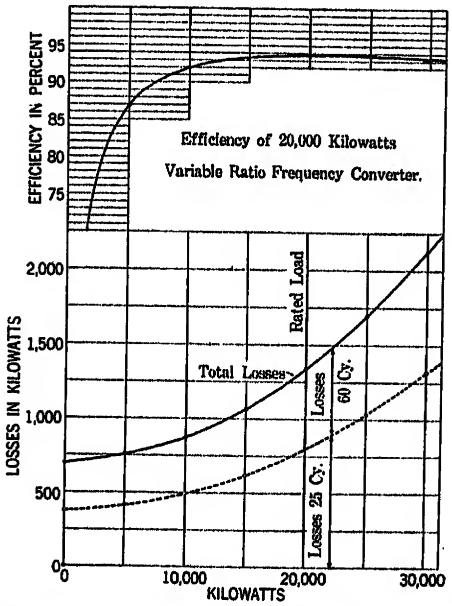

FIG. 4—PERFORMANCE OF THE 20,000-KW. CONVERTERS UNDER MAXIMUM LOSS CONDITIONS

machine. Normal operation of the induction machine is at 0.95 power factor over-excited.

In case of intentional or automatic opening of the oil circuit breaker in the primary leads of the main induction machine, all devices automatically reset to the proper re-start position except the load and power factor rheostats which must be re-set manually. A re-start can be made within ten seconds after an interruption.

Electrically operated "latched-in" oil circuit breakers are used throughout. These breakers have demonstrated their reliability fully, there having been not one instance of improper operation since installation.

The control board for the two sets is located in a quiet, well-lighted room about 100 ft. distant from the machine room. The board is of the frameless, dead-

front, stretcher-level-steel type and supports all controlling, protective, and metering devices.

The main machines are differentially protected. Overload protection is provided on the supply transformers. Each converter unit is served by two three-phase, 12,000-kv-a., water-cooled inertaire type transformers on both 25 and 60 cycles.

Fig. 4 shows the converter efficiency throughout the load range based on the conditions of greatest loss.

Fig. 5 shows a graphic wattmeter chart of the load

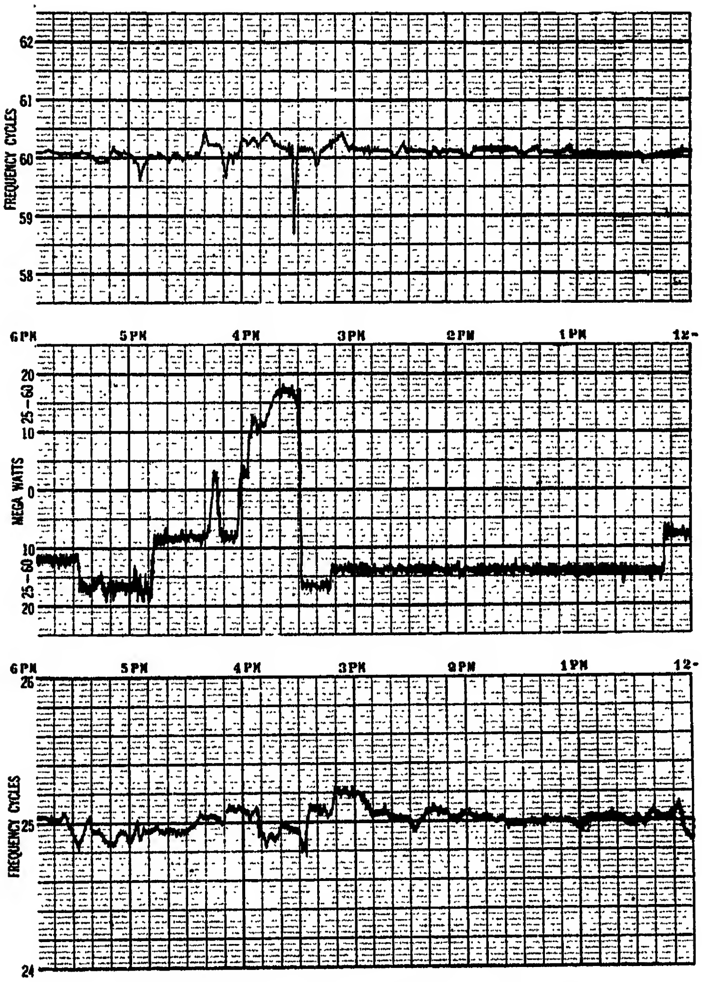

FIG. 5—SIMULTANEOUS LOAD TRANSFER AND 25-CYCLE AND 60-CYCLE FREQUENCY RECORDS

The top chart shows frequency of the 60-cycle bus; the middle chart shows megawatts, and the bottom chart shows frequency on the 25-cycle bus

on one converter when regulated by means of the automatic load regulator and simultaneous frequency records of the 25-cycle and 60-cycle systems. That part of the wattmeter curve below the center zero line represents a power flow through the converters from the 60-cycle to the 25-cycle system and that part above the zero line represents a conversion of power from the 25-cycle to the 60-cycle system.

The scale of the wattmeter is 25,000 kw. each side of the zero center line and it will be noticed that at 3:30 p. m. the load reversed through the converter changing from 17,000 kw. in one direction to 17,000 kw. in the opposite direction. This resulted from the loss of generating capacity on the 60-cycle system, which made it necessary to supply the deficiency from the 25-cycle system. Coincident with this power disturbance, the frequency of the nominal 60-cycle system decreased materially (to 58.7 cycles) but the nominal 25-cycle system evidenced no very appreciable reaction due to the relatively small change in power on this system, particularly from considerations of the 25-cycle system inertia.

Since installation both units have been in practically continuous operation. In the flood season, the surplus power from the 60-cycle system is supplied to the 25-cycle system through the converters. During the low water season, part of the 60-cycle system load is carried from the 25-cycle system through the converters. During the first 12 months operation *80 per cent* of the power through the converters was converted from 60 cycles to 25 cycles and *20 per cent* was in the opposite direction.

PART II

This second part of the paper will discuss a little more intimately the operation of a variable ratio frequency converter of the type described in the first part with particular reference to the relationship and the combined performance of its induction and load regulating machines.

The fundamental characteristics of a variable ratio converter can be rather simply evidenced by comparing it with the better known synchronous-synchronous type of converter.

The synchronous-synchronous type of set operates as a rigid tie between the interconnected power systems, in so far as the ratio of the system frequencies must be absolutely constant. If, for any reason whatever, the frequency of one of the systems has a tendency to change, a change in power flow through the set will result. The effect of this is to counteract the tendency of the one system to change frequency, by loading the system whose frequency tends to be high and unloading the system whose frequency tends to be low, until any tendency to depart from the exact frequency is equalized. In order to prevent the transfer power demands caused by the frequency variation tendencies from exceeding the maximum capacity of the interconnecting machines, it is obvious that the synchronous-synchronous set must have a certain minimum rating, determined by the capacities of the systems to be interconnected; otherwise normal changes in system conditions may cause pull-out of the set.

Fig. 6 illustrates the load conditions of two systems, and the effect of a synchronous-synchronous interconnection. In this figure the governor characteristics of the prime movers for a given setting are shown; at the left for station No. 1, at the right for station No. 2. The load is plotted from 0 along the horizontal axis.

The vertical axis gives the frequency in per cent of its nominal value. Let the points P_1 and Q_1 determine an initial load condition. The station loads are $P_1 R_1$ and $Q_1 R_1$, the system loads are $P_1 S_1$ and $Q_1 S_1$, and the load on the set is represented by $R_1 S_1$. Assume the load on system No. 2 increases; then new load conditions are established, as indicated by the points P_2 and Q_2. It is apparent that the frequency of the systems has decreased slightly and that the load increase of system No. 2 is partially supplied by station No. 1, thus increasing the load carried by the frequency converter. There is only one way to bring the system frequencies and the power transferred by the set back to their initial values—by setting the governors of station No. 2 for a higher load, so that the load distribution will now be determined by the points P_1 and Q_1.'

This demonstrates the following well-known fact: the power flow through a synchronous-synchronous converter can be adjusted solely by changing the

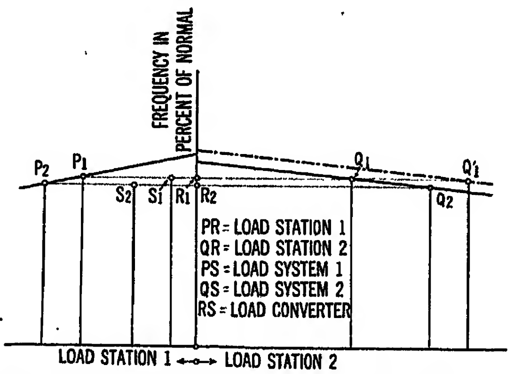

Fig. 6—Chart Showing Load Division

settings of the governors in the generating stations. If a substation contains more than one synchronous-synchronous set, the total load of the sub-station is likewise adjusted, although frame shifting devices make it possible to distribute this load between the individual frequency converter units as desired.

The arrangement of the variable ratio converter is essentially indicated by Fig. 7, consisting of a synchronous machine with d-c. exciter, a wound rotor induction machine, and a rotor excited commutator machine (regulating machine) with its separate exciter set.

The characteristics of the converter are very similar to those of a motor-generator set consisting of a synchronous machine coupled to a shunt wound d-c. machine with field adjusting rheostat. In both cases the speed of the set is determined by the frequency of the power system to which the synchronous machine is connected and the load transferred by the set is adjustable by load regulating equipment. For the synchronous-d-c. set the load is controlled by manipulating the field rheostat of the direct current machine; for the variable ratio converter, by varying the excitation of the regulating machine.

Fig. 8 shows speed-load characteristics representative of both a variable ratio converter and a synchronous-d-c. motor-generator set. These are "shunt" characteristics indicated with sufficient accuracy by a straight line for each setting of the load adjusting device. The load is plotted along the horizontal axis. To the right

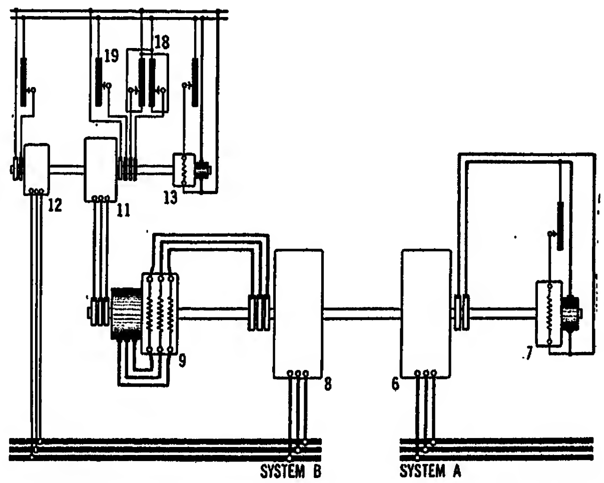

Fig. 7—Fundamental Diagram of the Variable-Ratio Frequency Converter

The reference numbers correspond to those in the complete wiring diagram shown in Fig. 3

6 Main synchronous machine
7 Main d-c. exciter
8 Main induction machine
9 Load regulating machine
11 Synchronous exciter
12 Auxiliary synchronous motor
13 Auxiliary d-c. exciter
18 Load rheostat
19 Power factor rheostat

of point O the adjustable machine (induction or d-c. machine) is motoring and to the left generating. The speed of the set is plotted along the vertical axis. As shown, for any setting of the load adjusting device,

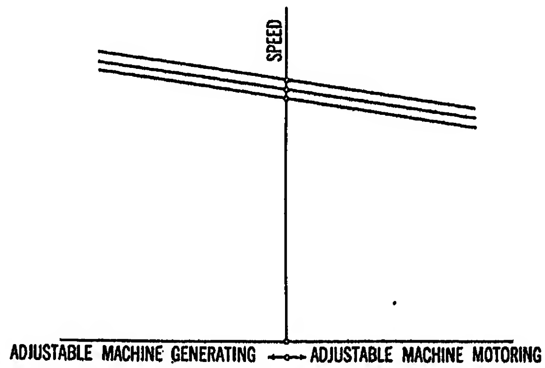

Fig. 8—Speed Load Characteristics of Converter and Motor Generator

decreasing speeds result inherently in decreasing generator-load or increasing motor-load.

Changing the setting of the load adjusting equipment results in practically a parallel displacement of the sloping "shunt" characteristic and with each setting there is a corresponding no-load speed. Within the

range covered by such a "family" of characteristics as provided by the design of the regulating equipment the set can be adjusted so as to carry any desired power flow (in either direction) at any speed. A load regulator provides automatic manipulation of the load adjusting apparatus so as to maintain a constant load in spite of speed variations.

In the case of a variable ratio frequency converter, the vertical axis of Fig. 8 must express the ratio of the synchronous speeds of the synchronous and induction machines instead of the rotational speed of the set. This is because the load transferred by the set will be entirely determined by the speed relationship between the rotor and the flux of the induction machine for each setting of the load regulating equipment. Variations

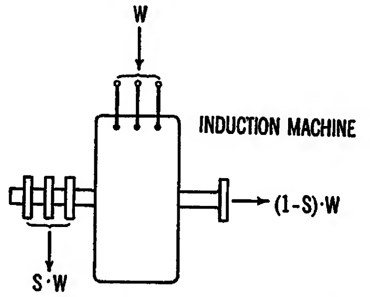

Fig. 9—Diagram of Induction Machine

	Line power (W) is positive	Line power (W) is negative
Slip (S) is negative. Induction machine operates above synchronism.	(1) Shaft power $(1 - S)\ W$ is positive. Induction machine operates as motor. Rotor power $S\ W$ is negative. Regulating machine operates as generator.	(2) Shaft power $(1 - S)\ W$ is negative. Induction machine operates as generator. Rotor power $S\ W$ is positive. Regulating machine operates as motor.
Slip (S) is positive and less than unity. Induction machine operates below synchronism.	(3) Shaft power $(1 - S)\ W$ is positive. Induction machine operates as motor. Rotor power $S\ W$ is positive. Regulating machine operates as motor.	(4) Shaft power $(1 - S)\ W$ is negative. Induction machine operates as generator. Rotor power $S\ W$ is negative. Regulating machine operates as generator.

in the frequencies of either one or both of the interconnected power systems will change this speed relationship, the ratio of the synchronous speeds being proportional to the frequency ratio. Assume for instance that the frequency impressed on the synchronous machine remains constant, and the frequency impressed on the induction machine varies; then the load will vary with the ratio of the synchronous speeds although the speed of the set remains the same.

The shunt characteristics of the variable ratio converter have a very slight slope. This means that, without load adjustment, small variations in frequency ratio will cause large changes in the load transferred by the converter, and thus the variations in frequency ratio will be partially but not entirely counteracted. In the case of the synchronous-synchronous converter, as has been stated before, any tendency to depart from the exact frequency ratio will be wholly counteracted by a change in the load transferred.

Except for its load reversibility, a variable ratio set is closely analogous to a synchronous generator driven by a prime mover, the induction machine with its load adjusting apparatus simulating the prime mover with governing equipment. In either case the operating characteristics of the synchronous machine are similar and in no way peculiar. Hence, the following will be restricted to a discussion of the induction machine and the load adjusting apparatus as they provide the essential and interesting characteristics of an adjustable load variable ratio converter.

The wound rotor induction machine as represented by Fig. 9 will be considered first. Let W represent the line power which may be input to (positive) or output from (negative) the primary of the machine. Neglecting the losses of the machine, this power will partly appear at the shaft in the form of mechanical power and the remainder will be converted by transformer action to the secondary or rotor winding and appear at the collector as electrical power. The relative values of these two components of the line power are determined by the speed relationship of the flux and the rotor, or in other words, by the slip of the machine. Letting S represent the slip, the shaft power is equal to $(1 - S)$ W and the collector power to $S\ W$. Collector power must be either absorbed or supplied by external equipment. The sign of W, and the value and sign of S determine the operating possibilities of the induction machine and regulating apparatus as given in the table accompanying Fig. 9.

For instance, an induction machine with a constant resistance in its rotor circuit will run at synchronous speed at no-load. If loaded, its rotor will slip positively or negatively so that the rotor power ($S\ W$), which must provide the ohmic losses in the rotor circuit and is dissipated entirely as heat, will be positive. Therefore, under this operating condition only cases 2 and 3 of the table are possible, showing that the machine can run only as a motor below synchronism and only as a generator above synchronism.

However, if an active source of energy, such as a so called "regulating machine" is inserted in the rotor circuit of the induction machine, its rotor power ($S\ W$) may be negative as well as positive, regardless of whether the slip is positive or negative.

The fundamental operating principles of such a regulating machine will be explained as follows: Assume that a wound rotor induction machine, with its stator energized and its rotor circuit open, is operated at some definite speed. Then the frequency and voltage appearing at the rotor leads will be proportional to the slip. If an external voltage of the same slip frequency, and equal and opposite to the internal

rotor voltage is applied to the collector, no current will flow in the rotor circuit, due to the voltage balance, and the conditions in the main induction machine remain unchanged. Increasing or decreasing the magnitude of the external voltage will cause a flow of rotor current in phase or in phase-opposition with this voltage so that the ohmic drop will maintain the voltage balance. The product of internal rotor voltage and current represents the rotor power ($S\,W$); that is, the main induction machine now carries a corresponding load (W). In this way the main induction machine may be forced to carry various desired loads, by adjusting the magnitude of the external voltage applied to its collector, irrespective of the slip.

The above describes the effect of an external voltage in phase or in phase-opposition with the internal rotor voltage. Similarly, if the external voltage is given a component in phase-quadrature with the internal rotor voltage, it will result in a quadrature component of rotor current which inherently will be neutralized by a corresponding reactive current component in the primary of the induction machine. In other words the quadrature component of the external voltage applied to the collector will influence the power factor of the primary, but not the energy load carried by the machine. From this it is obvious that control of the external rotor voltage (regulating machine voltage) in quadrature directions provides a means of adjusting the watt and wattless components of the primary current. For the sake of simplicity the foregoing explanation intentionally neglects the effect of the reactance and the primary resistance of the induction machine. The principal influence of these factors is to cause a small phase shift in the internal rotor voltage, depending on the load, thus changing slightly its relationship with the in-phase and quadrature components of the external voltage. As a result the in-phase component will affect to some extent the power factor and the quadrature component the energy load of the machine. With low slip values these effects are immaterial.

External rotor voltages of the required characteristics as previously outlined can be obtained from a suitably designed regulating machine and by its use the operating range of the induction machine will be enlarged so as to include all four operating possibilities of the table accompanying Fig. 9.

For the machine arrangement being considered, the regulating machine is directly coupled to and is wound for the same number of poles as the main induction machine. The regulating machine has a uniform airgap and evenly distributed windings on stator and rotor. The stator has a three-phase, two-layer winding with 60-deg. phase belts and 180-deg. coil throw. The rotor is very similar to an ordinary d-c. armature and has a two-layer lap winding with 180-deg. coil throw connected to a commutator. The current is collected from the commutator by three sets of brushes spaced 120 electrical degrees apart, which form the three commutator phases and are connected to the three stator phases as shown by Fig. 10. The turn ratio of the stator and rotor windings is chosen so that these two windings exactly compensate each other provided the brushes are in the proper position on the commutator. This means that any system of three-phase currents flowing through the combination of series connected stator and commutator phases cannot create any magnetic flux because the stator and rotor ampere-turns neutralize each other completely.

The magnetic flux required in the machine is created exclusively by a third winding of the three-phase type which is evenly distributed on the rotor and is connected to a collector. This exciting winding is energized by a source having a frequency exactly equal to that of the line energizing the stator of the main induction machine and produces a sinusoidal flux which rotates relative to the rotor of the regulating machine with synchronous speed against mechanical rotation. Consequently the flux rotates with slip speed relative to the stator and a

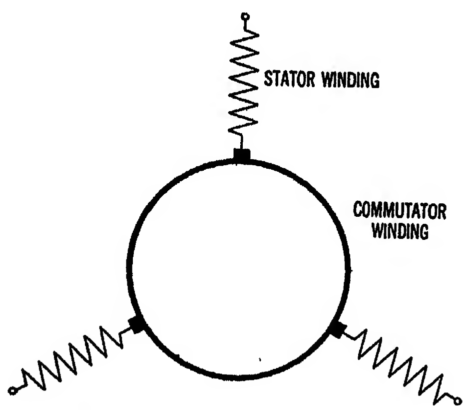

Fig. 10—Fundamental Diagram of Main Circuits of Regulating Machine

three-phase voltage having a frequency at all times equal to the frequency appearing at the collector of the main induction machine is induced in the combination of series connected stator and commutator phases. The magnitude of this voltage is proportional to the flux intensity and the rotational speed of the machine.

Referring again to Fig. 7, assume that the leads between the collector of the main induction machine and the stator terminals of the regulating machine are disconnected. Then at the collector of the induction machine a three-phase voltage appears which has a magnitude and frequency proportional to the slip, and a three-phase voltage of the same frequency exists at the terminals of the regulating machine. By properly adjusting the magnitude and phase of the collector voltage of the regulating machine, its stator terminal voltage can be made equal and opposite to the collector voltage of the induction machine. Then if the main secondary circuit is closed no electrical change will occur and by in-phase and quadrature adjustments of the regulating machine collector voltage the main induction

machine can be forced to carry the desired energy and wattless loads.

The regulating machine operates either as a motor or as a generator converting the electrical power at its stator terminals into mechanical power at the shaft or *vice versa*; no power is transferred to or from its exciting winding. This will be more readily understood if it is realized that the flux in the regulating machine is due entirely to the current in the exciting winding and, therefore, will be in phase with this current. However, the voltage induced in the exciting winding will be in quadrature with the flux and consequently with the exciting current. Hence the exciting current will be wattless current, lagging relative to the voltage impressed on the collector of the regulating machine, except for a small watt component supplying the copper losses in the exciting winding and the core losses. It is apparent that the source (synchronous exciter) energizing the regulating machine needs to furnish only a little energy for these losses in addition to a considerably greater amount of lagging wattless for excitation.

The synchronous exciter is driven by a synchronous motor, having the same number of poles, whose stator is connected to the same source as is the primary of the main induction machine. By this arrangement the frequency of the excitation for the regulating machine will always be correct. The synchronous exciter is essentially a three-phase synchronous generator with a distributed field winding in two separate circuits each connected to individual collector rings. When energized by direct current the two circuits of the field winding create two magnetic fields at 90 deg. with each other, which induce the two in-quadrature components of the exciting voltage needed for the regulating machine. A definite phase relation must exist between these voltage components and the primary voltage of the main induction machine; this is properly established experimentally and fixed permanently by setting the coupling between the synchronous exciter and its driving motor before the converter is put into service.

The two component fields of the exciter are designated as "load field" and "power factor field," this nomenclature expressing their purpose in controlling the energy and reactive loads respectively of the main induction machine. A rheostat of the potentiometer type controls the excitation of the load field; this "load rheostat" is actuated normally by the automatic load regulator. The field rheostat for the control of the power factor field is of the ordinary series type, as the small slip of the main induction machine makes reversal of the power factor field current unnecessary. The d-c. excitation for the synchronous exciter and its synchronous driving motor is supplied by a small d-c. generator. These three machines constitute the auxiliary set of Fig. 7.

To explain more simply the functioning of the regulating machine its exciting winding has been represented as being a separate winding on the rotor. Normally this winding is common with the commutator winding, resulting in an arrangement very similar to that on the rotor of a synchronous converter.

The excitation of the regulating machine could be obtained more directly through a static voltage transformation (with ratio and phase angle control) from the power system to which the stator of the main induction machine is connected. However, the use of an auxiliary synchronous exciter set to supply this excitation results fundamentally in a main induction machine which is more stable at time of system disturbances as its rotor excitation is, within the pull-out torque of the synchronous motor driving the auxiliary set, practically independent of system voltage. Furthermore, load and power factor field adjustment by means of rheostats is very reliable and simple and compares favorably with ratio and phase angle control of the excitation voltage through complicated transformer equipment or by means of exciters having commutator brush shifting mechanisms.

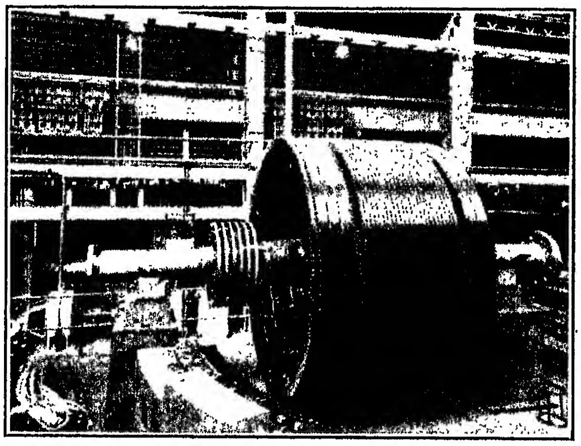

Fig. 11—Phase Wound Rotor of the 23,000-Kv-a. Induction Machine

In the foregoing pages the fundamental arrangement and operating characteristics of a variable ratio frequency converter of the type installed in the Lockport Substation have been discussed in some detail. The following is intended to show the actual construction and appearance of the more interesting parts of the Lockport converters and to point out the departures from the simplified arrangement of Fig. 7.

The rotor of the main induction machine is shown in Fig. 11. The coils were completely formed and insulated before being put in place in the half closed slots. Both ends of each of the three rotor phases are connected to individual rings of the six-ring collector, this phase separation being advantageous in connection with the construction of the regulating machine in two units.

Fig. 12 shows the stator of a regulating machine unit. The coils of the three-phase stator winding are embedded in fully closed slots. In the top of the slots is a

high resistance squirrel-cage winding for damping high harmonic fields which might disturb commutation.

Fig. 13 is a view of the rotor of a regulating unit. The coils are connected to the commutator bars through high resistance leads in order to minimize the circulating current in the coils undergoing commutation. The banding on the front of the commutator

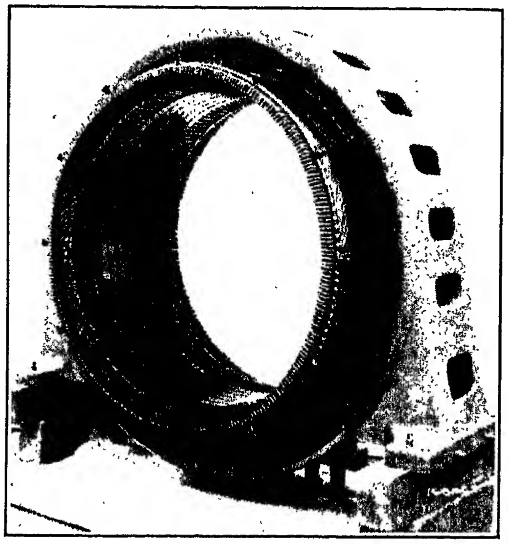

Fig. 12—Stator of a Load Regulating Machine Unit

covers involute cross connections between commutator bars. The excitation leads from the rotor winding connect to a six-ring collector.

The auxiliary exciter set is shown by Fig. 14. The center machine is the synchronous exciter with the six leads of the three separate stator phases in the fore-

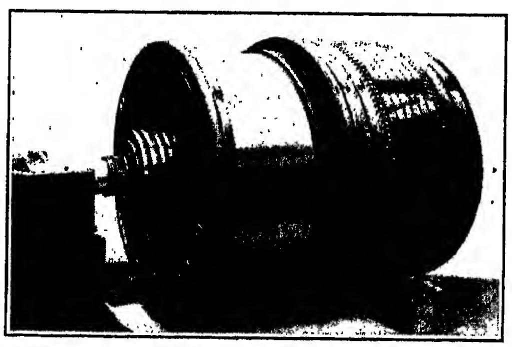

Fig. 13—Rotor of a Load Regulating Machine Unit

ground. To the left are the two pairs of collector rings for the load and power factor fields. To the right is the coupling used to adjust the phase angle relationship between the synchronous exciter and the synchronous driving motor. At the extreme left is the small d-c. exciter.

Attention has been called to the application of a double unit regulating machine and to the use of three separated phase windings on the main induction rotor and in the synchronous exciter stator of the Lockport converters. The diagram exemplifying the rotor connections involved by this arrangement appears in Fig. 15. In the center of the diagram are represented the three separated rotor phases of the main induction machine; at either side is the rotor winding of a regulating unit. The diagram is bipolar; heavy lines represent windings, and small circles indicate the location of the collector taps. For the sake of simplicity the stator (compensating) windings of the regulating units have been omitted.

Tracing through each main rotor phase it is seen that one phase lead terminates on the commutator of the left unit and the other lead of the same phase on the

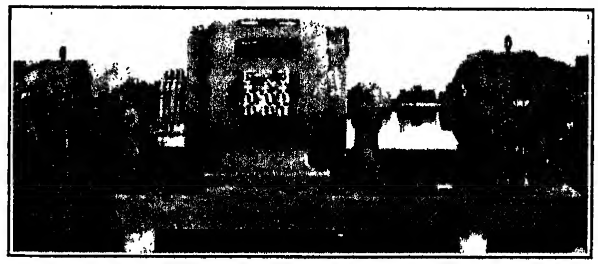

Fig. 14—The Auxiliary Synchronous Exciter Set

commutator of the right unit at points which electrically are diametrically opposite. The stator phases of the synchronous exciter are not shown, although their connections to the rotor windings of the regulating units are shown by the six collector taps $R_1 - R_4$, $R_2 - R_5$, and $R_3 - R_6$ corresponding to the exciter phases $1 - 4$, $2 - 5$, and $3 - 6$.

The three collector phase taps R_1, R_2, and R_3 are spaced 120 electrical degrees apart; the phase belts between $R_1 - R_4$, $R_2 - R_5$, and $R_3 - R_6$ do not cover 180 electrical degrees but are less than a full pole pitch. This chording of the phase belts necessitates six collector taps but it minimizes the magnitude of harmonic fluxes created by the exciting current which would be detrimental to commutation. The two three-phase commutator winding systems, excited in parallel and connected in series through the main rotor phases, are electrically equivalent to the winding system of one

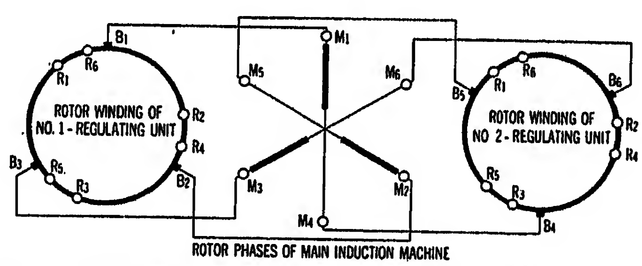

Fig. 15—Fundamental Connection Diagram of Main Rotor Circuits

rotor excited machine with six commutator phases instead of three.

It is interesting to consider the various factors affecting the selection of the most suitable arrangement of a variable ratio converter. The induction machine

may be built for either one of the systems to be interconnected; however, one of the systems may have advantages which should be recognized in individual cases. For instance, if the converter is to interconnect a three-phase and a single-phase system, it usually will be more desirable to connect the induction machine to the three-phase and the synchronous machine to the single-phase system. If the converter is to interconnect two three-phase systems, the induction machine should be connected to the system offering the most favorable conditions for the design of the load regulating equipment which generally is the lower frequency system. The number of poles of the main synchronous and induction machines are preferably chosen so as to obtain equal or nearly equal synchronous speeds at nominal frequencies in order to minimize the slip of the induction machine and consequently the rating of the regulating apparatus. For instance, if the converter is to interconnect a 25-cycle and a 60-cycle system, and is to have the synchronous machine on the 60-cycle end, the following speeds and pole combinations can be chosen.

Speed rev. per min.	Synchronous machine poles (60 cycles)	Induction machine poles (25 cycles)	Slip induction machine (at nominal frequencies)
720	10	4	+4.00%
514	14	6	−2.86%
360	20	8	+4.00%
300	24	10	0%

The fourth column gives the slip of the induction machine at nominal frequencies (positive slip indicates under-synchronism and negative slip over-synchronism).

Variable ratio frequency converters will be fittingly selected for application where the operating economy or convenience of load adjustment at the converter justifies their somewhat higher cost and slightly lower efficiency. There will be other instances where necessity dictates the use of such converters in order to provide a sufficiently reliable connection between systems. It is impossible to specify generally the system conditions requiring variable ratio converters. In determining the proper type and size of any form of interconnecting equipment not only the capacity of the systems but also the general and specific capacity of the other metallic and electro-magnetic connections within a system should be considered. Recent experience with automatic frequency regulators reveals the fact that normal frequency fluctuations can be controlled within very close limits by load regulation of a surprisingly small percentage of system capacity. From this fact it is apparent that the normal tendencies of two interconnected systems to depart from a constant frequency ratio can be counteracted by at least a correspondingly small transfer of load from one system to the other. Actual operating experience has shown that two power systems may be connected together successfully by synchronous-synchronous frequency converters having a capacity of only ten per cent of the capacity of the smaller system. Where the capacity of the desired interconnecting apparatus is less than ten per cent some uncertainty exists regarding the suitability of the more rigid types of converters and the application of variable ratio converters should be carefully considered.

Discussion

P. W. Robinson: The presentation of this paper following those of Mr. Encke and Mr. Burnham last year at the New Haven meeting is indicative of the growing demand for large conversion units for load transfer between power systems. In the meantime, a 20,000-kw. variable-ratio set with Scherbius type of load regulating machine has been delivered to the Buffalo General Electric Co., and two more of the same capacity are under construction for the Union Electric Light and Power Co. for installation at their Page Avenue substation in St. Louis. An interesting feature of the latter installation is that the induction units of the sets, which are to be located at considerable distance from a main generating station, are to be so controlled as to make the reactive kv-a. respond to system voltage. Thus a Scherbius-controlled induction motor, in addition to controlling load transfer, will be used to minimize line voltage variations by regulation of the reactive kv-a. it supplies to or draws from the power system. A further interesting development in connection with the control of these sets is that starting motors will be used to bring them to approximately the synchronous speed of the induction unit and this unit is excited through its rotor by the Scherbius machine before its primary is connected to the power system. This arrangement makes it possible to use a starting motor with a more suitable secondary voltage than can be used on the main induction unit, thus eliminating high-tension switching apparatus in the secondary circuit for starting and reducing the size of the secondary control. Further important advantages are that the induction of high secondary voltage in the main induction unit and the strains incident to connecting the unexcited primary to the line are both avoided.

The most important difference between the type of set described in the paper and the Scherbius controlled set is that in the former the excitation for the regulating machine is unaffected by variations in system voltage, while in the latter case it is proportional to the system voltage. The constant voltage supply enables the induction machine to transfer more power to the system in case of voltage disturbances, up to the limit of pull-out torque of the synchronous machines. Precautions must be taken, however, that this maximum power limit is not exceeded.

As a result of the supply of excitation for the Lockport set at line frequency, a total of 350 kv-a. exciter capacity is required, while the excitation for the Scherbius control set of the same rating for Buffalo, being supplied at slip frequency, amounts to only 14 kv-a.

A. Van Niekirk and W. H. Rodgers: Mr. Robinson's discussion is of interest and value, being expressive of a slightly different point of view. In that connection it may be of equal interest to mention some of the pertinent considerations which influenced the design of the Lockport Converters.

A starting motor is logically used as an expedient where the inrush kv-a. incident to the starting of a converter (or condenser) is paramount and cannot be limited otherwise to an acceptable value. There may be other cases where a starting motor will offer economic advantages, for instance where the locked rotor voltage of an induction machine is very high. However, with the Lockport converters, the design is such that using the main induction machine for starting requires only a moderate and acceptable current inrush (corresponding to 10,000 kv-a.).

Furthermore the rotor voltage of the induction machine (4080 volts per phase) is not so high that a starting motor could have offered any economic advantages.

In this connection it should be realized that the fill-factor of the rotor slot for the 4080-volt winding will not be appreciably smaller than the slot fill-factor for a 500-volt winding, because the heavy rotor copper straps of a machine of this size require a certain minimum insulation thickness in order to obtain a coil insulation which is sufficiently strong from mechanical considerations.

The use of a starting motor results in the addition of another direct-connected machine; it increases the constant losses; and makes bearing oil pressure starting equipment necessary. Moreover, the main induction machine is inherently more reliable than a short-time rated starting motor and this fact is particularly momentous in connection with the importance of this interconnecting equipment.

It is most unusual to hear advocated that it is advisable to avoid the strains incident to connecting an unexcited induction machine to the line; it is common practise to start wound-rotor induction motors of even the highest ratings directly, using suitable secondary control. This method is generally successful, and has been during the 18 months of regular operation of the Lockport converters. When a starting motor is used, this motor will be started by the same method; however, the strains incident to energizing its stator will be relatively higher than for the main induction motor if used for starting, because the short-time rated starting motor will be of less sturdy construction.

Further it should be emphasized that to connect the induction machine primary to the line, after exciting the rotor winding by the regulating equipment, does not necessarily require a starting motor. It can be much more reliably accomplished by starting with the main synchronous machine in combination with a starting transformer in cases where the converter can or must be started from the synchronous end.

The kv-a. ratings of the a-c. exciters for the Lockport and Scherbius types of converters are not at all indicative of the comparative physical size, complexity, or performance of these exciters. As a matter of fact, the 350-kv-a. Lockport exciter is no larger over-all than the 14-kv-a. Scherbius exciter; the former is an ordinary synchronous machine of simple construction rather than a frequency converter with commutator and complicated brush-shifting mechanism.

It is gratifying to hear that due acknowledgment is made of the inherent superiority of regulating machine excitation derived from a source less directly affected by system voltage disturbances than is the case where this excitation is proportional to system voltage.

Theory of a New Valve Type Lightning Arrester

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Synopsis.—Theory and experimental data are given on the properties of discharges confined to small holes, such as the pores of a naturally porous material. The characteristics of these discharges are such that they are well suited for utilization in a valve type lightning arrester.

* * * * *

I. The Valve Type Arrester

A VALVE type lightning arrester is an apparatus which passes current freely for impressed voltage in excess of a certain value, and which ceases to carry current almost completely for impressed voltage less than a certain other value. If the impressed voltage is increased continuously from a low value, that voltage at which current begins to be passed freely is called the breakdown voltage. After the breakdown voltage is exceeded, if the voltage is decreased continuously, the arrester will generally continue to pass current relatively freely until a lower value of voltage is reached at which discharge of current substantially ceases. This voltage at which current flow nearly stops, we shall call the cut-off voltage of the valve arrester.

The cut-off voltage of a valve arrester is usually not sharply defined, since a small current may flow down to zero voltage. For practical purposes, however, it is that voltage at which the current flow is so small that it may be readily interrupted by a simple series spark-gap structure on alternating current. The breakdown voltage of the arrester is not necessarily the largest voltage which may appear across the arrester. The characteristic of the arrester may be such that to pass several hundred or a thousand amperes, the voltage may rise to a value greater than the breakdown voltage. The largest voltage which appears across an arrester during a normal discharge we shall call the maximum voltage of the arrester. The ratio of this maximum voltage to the cut-off voltage, we shall call the voltage ratio of the arrester.

It is evident that the voltage ratio of a valve type arrester determines its protective value on an electrical system. For the cut-off voltage must be proportioned to the normal working voltage of the system, and then the maximum voltage of the arrester will determine the stress which the system insulation will receive during lightning. The characteristics of electrical insulation under impulse voltages are such that a properly applied arrester with voltage ratio of two or three will give almost perfect protection. A valve arrester with a voltage ratio of ten or more will have little protective value.

A valve type arrester must change from a good conductor to a relatively good insulator over a moderate change of voltage. The field of discharges in gases would seem to offer the best possibilities for the realization of these characteristics. Examination of the field reveals, however, that although valve effects are generally present, their voltage ratio is not sufficiently low to be useful except in a few special cases or arrangements.

To illustrate this, consider a simple spark-gap, one cm. long, between spheres or planes in air at normal pressure and temperature. The breakdown voltage is 30,000 volts. After breakdown, its properties are that of a one cm. arc shown in Fig. 1.[2] Here we see that the

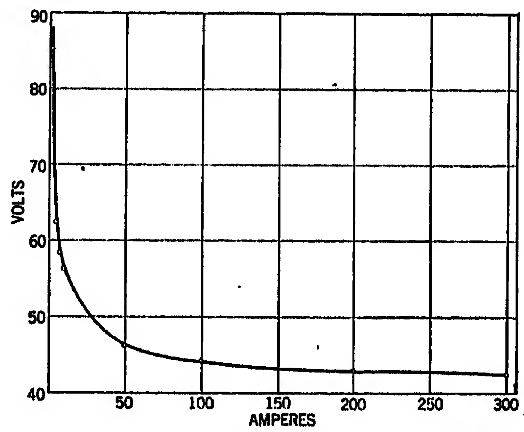

Fig. 1—Characteristic of a One Cm. Long Arc, Copper Electrodes

minimum voltage capable of maintaining the discharge is very low, of the order of about 40 volts, and that this minimum occurs for very large currents. Hence, the cut-off voltage of such a spark-gap used on systems capable of delivering large current would be 40 volts, and the voltage ratio would be 750. If the electrical system is not capable of delivering large currents, the voltage for maintaining the arc will be greater, but even if the current is limited to 10 amperes, the arc voltage will still be only 56 volts, and the voltage ratio will be 535.

It is clear from this example that the volt-ampere

1. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

2. Plotted from equations of Nottingham. *Phys. Rev.*, 28, 1926, p. 764.

characteristic of the discharge which follows breakdown must be studied to determine the lowest voltage which will maintain the discharge under given conditions. This will be the cut-off voltage of the arrester constructed utilizing this type of discharge. It is also clear that types of discharge must be sought which require a high voltage for their maintenance. In this

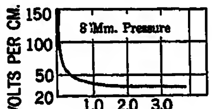

FIG. 2—GRADIENT IN POSITIVE COLUMN IN DISCHARGE IN NITROGEN WITH CURRENT DENSITY OF 0.26 AMPERES, CM.^{2} IN TUBES OF VARYING CROSS—SECTIONAL AREA

way the cut-off voltage may be brought up to the order of magnitude of the breakdown voltage, and thus a low-voltage ratio may be obtained.

In the autovalve arrester,[3] for example, by the use of electrodes of relatively high resistivity, the discharge is constrained to remain in the form of a glow instead of being permitted to take the form of an arc which is the more usual form at atmospheric pressures. The glow is distinguished from the arc in that it requires a minimum of several hundred volts for its maintenance as compared with about 20 volts for a very short arc. By using very short spacings between the high resistivity electrodes, the breakdown voltage is made to be

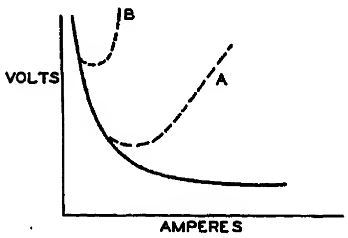

FIG. 3—VOLT-AMPERE CHARACTERISTIC OF DISCHARGE IN THE OPEN AND IN HOLES OF DIFFERENT SIZES

also only several hundred volts, and thus a very low voltage-ratio is obtained.

II. ELECTRICAL DISCHARGES IN HOLES AND FINE CAPILLARIES

Another method of obtaining a discharge which requires for its maintenance a voltage comparable with that required to initiate the discharge has been discovered. It has been found that the voltage required to maintain a discharge can be raised to high values by confining the discharge to narrow passages with insulating walls. This is well known in the case of discharges in Geissler tubes, where the gradient required by the positive column at constant current density varies inversely with the diameter of the circular glass tube as shown in Fig. 2.[4] The reason for this lies in the fact that ions are lost from the discharge principally by recombination on the walls of the tube, and the ratio of the wall perimeter to the tube section increases as the diameter decreases. Not only is the gradient increased by confining the discharge, but the volt-ampere characteristic may be changed from a falling one to a rising one.

In Fig. 3, the heavy line indicates the volt-ampere characteristic of a discharge in the open at atmospheric pressure. The dotted curve *A* indicates that of a discharge confined to a circular hole. For small currents, where the natural section of the discharge is less than that of the hole, the walls of the hole have little influence upon the discharge, and the voltage is the same as that for a discharge in the open. When the discharge fills the hole, however, the voltage is increased and the curve *A* departs from the solid curve. With further increase of current, the confining action of the hole becomes so great that the voltage increases with increasing current. Curve *B* in Fig. 3 indicates the effect of a smaller hole. The departure from the solid curve

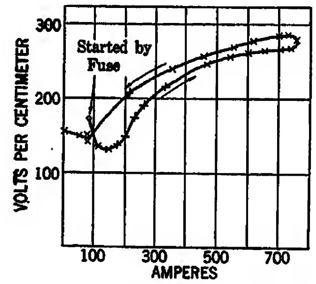

FIG. 4—CHARACTERISTIC OF DISCHARGE IN 0.178 DIAMETER HOLE IN SOAPSTONE

for the discharge in the open occurs at smaller current and higher voltage.

From these curves we are led to believe that for discharges confined to holes at atmospheric pressure there is a minimum voltage which occurs at a relatively small current, and that with smaller holes this minimum voltage is greater, and occurs at smaller currents. This is confirmed by the work of R. C. Mason who has plotted the volt-ampere characteristic shown in Fig. 4 of a discharge in a 0.178 cm. diameter hole in soapstone, the discharge being started by a fine fuse wire, and the current and voltage values measured from an oscillogram. The existence of a minimum voltage gradient of considerable magnitude and occurring at a small value of current is brought out in this curve. Mason has also obtained data showing that the minimum voltage gradient is increased as the size of the hole is decreased. In Fig. 5, the crosses indicate the minimum voltages observed by Mason for discharges in slots with soapstone walls of varying width. These

3. J. Slepian, TRANS. of A. I. E. E., XLV, 1926, p. 169.

4. W. Matthies and H. Struck, *Handb. d. Physik*, Vol. XIV, p. 274.

discharges were started by fine fuse wires in a 60-cycle circuit and oscillograms taken of current and voltage. The circles in Fig. 5 indicate the results obtained by the authors for very narrow slots between glass plates. These discharges were started disruptively by application of very high voltage, and a cathode ray oscillogram was taken of the volt-ampere characteristics.

III. Discharges in Naturally Porous Materials

The data of Fig. 5 show that to obtain minimum discharge voltage gradients of the order of several thousand volts per cm. at atmospheric pressure and thus of an order of magnitude beginning to be comparable with breakdown voltage gradients, the passages to which the discharges are confined must have sections with linear dimensions less than 0.001 cm. With such small dimensions, the current carried by a passage with the voltage gradient maintained at breakdown value will be

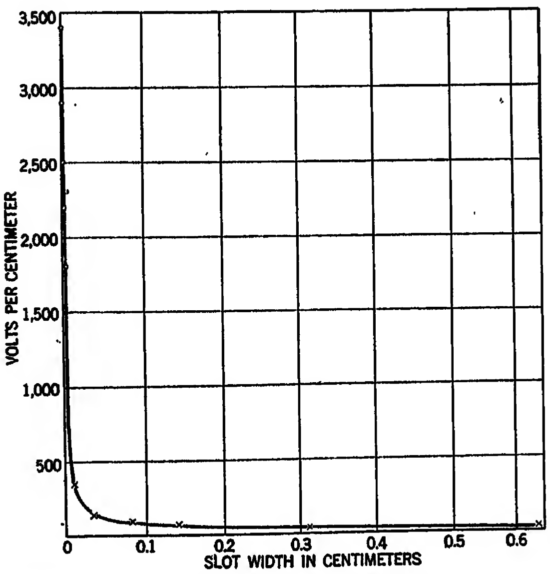

Fig 5—Minimum Voltage Gradient for Discharges in Slots

very small. For lightning arrester purposes, therefore, it will be necessary to use a very large number of these very fine passages in parallel. It would not be practical to construct or assemble directly such a multitude of fine passages or channels. Materials can be made, however, which are naturally permeated by fine pores, whose sections are of the required dimensions.

In Fig. 6, for example, is given a cathode ray oscillogram showing the course of the voltage with the time, for a discharge from a condenser through a piece of red building brick, 7 mm. thick. Breakdown occurred at about 22,500 volts. The voltage then dropped sharply to about 10,000 volts, and then dropped slowly to about 5000 volts, where it remained nearly stationary as the current decreasd. This indicates that most of the pores had minimum discharge voltages or cut-off voltages of about 5000 volts. In terms of gradients, breakdown occurred at 32,000 volts/cm. and cut-off for most of the pores at 7100 volts/cm. The brick appeared to be uninjured by the discharge and the experiment could be repeated, reproducing the oscillogram and thus indicating that the discharge had passed only through the pores of the brick without affecting the solid material.

Before showing volt-ampere oscillograms of discharges through porous materials, it will be well to

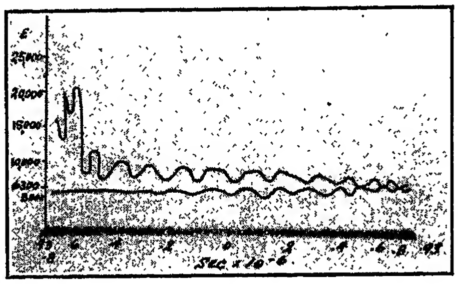

Fig. 6—Discharge through Piece of Red Brick

consider what characteristic may be expected from consideration of the volt-ampere characteristic of a single fine hole as shown in Fig. 3. In Fig. 7A, the full curve shows the static volt-ampere characteristic of a dis-

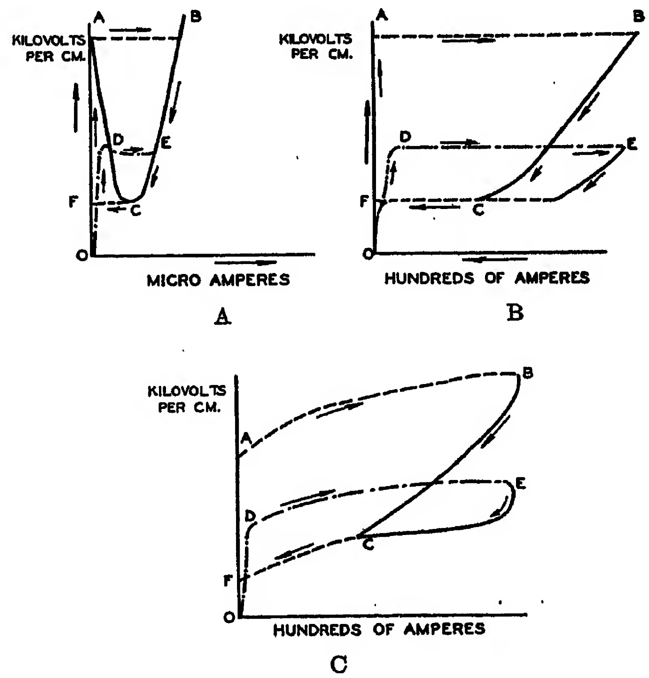

Fig. 7—Characteristics of Discharges in Five Holes

charge in a very fine long hole. Breakdown occurs at A, and the minimum or cut-off voltage is shown at C. If the voltage impressed along the hole is raised to the breakdown point A, and then held at this value, the current will at once build up to that corresponding to B, which is the other intersection of the horizontal through A with the static characteristic. If the voltage is now lowered, the current will decrease following the curve $B\,C$ until the cut-off point C is reached. If now the voltage is lowered only slightly, and held constant, the

discharge can no longer be maintained, and the current decreases rapidly to zero along the line $C\ F$. Raising the voltage to the breakdown value and then lowering it, thus causes the loop $O\ A\ B\ C\ F$ to be traced.

If now a hundred million fine holes, each having identically the characteristic of Fig. 7A, are used in parallel, it is clear that when the voltage is raised to the breakdown value each individual hole will break down

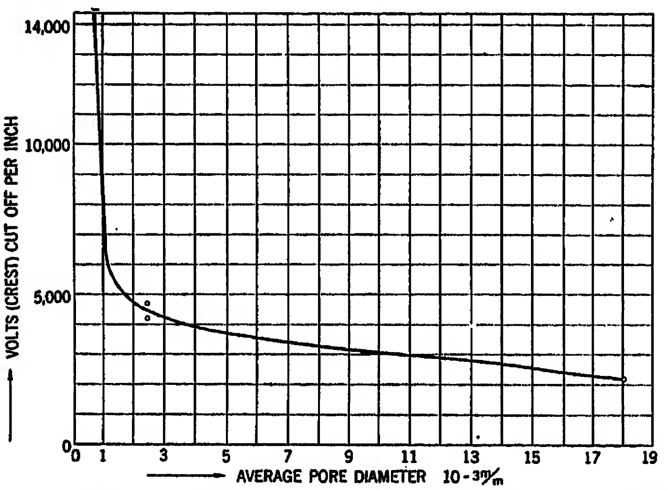

Fig. 8—Relation between Cut-off Voltage and Average Pore Diameter

carrying its own few microamperes, and that when the voltage is lowered to the common cut-off value each hole will cease carrying its minute current. A volt-ampere loop $O\ A\ B\ C\ F$ is obtained for the multitude of holes entirely similar to that for a single hole except that the current scale is in hundreds of amperes instead of microamperes. Fig. 7B.

In an actual porous material, the hundreds of millions of fine holes which are its pores will not all have the same breakdown voltage. The volt-ampere loop will therefore be modified as shown in Fig. 7C. Current will first flow when the voltage reaches A, the breakdown voltage of the pores having the lowest breakdown value. As the voltage is further increased the current increases in two manners. First, the current carried by those pores which are already broken down increases. And also, with increase of voltage, the breakdown value of more pores is exceeded and these additional pores begin to carry current. Thus, the upper portion of the volt-ampere loop slopes upward as in Fig. 7C.

The pores of an actual porous material will also not all have the same minimum or cut-off voltage. This will cause the lower branch of the volt-ampere loop to be modified as in Fig. 7C. As the voltage is lowered from the point B, the current decreases because the current in each pore decreases. When the point C is reached, some of the pores stop carrying current altogether because their cut-off voltage has been reached. Along the portion $C\ F$ more and more of the pores cease carrying current, and at F, the cut-off of the last pore is reached.

Regarded as a lightning arrester, the breakdown voltage of the porous material is the breakdown voltage of the pore having the lowest breakdown, and the cut-off voltage of the porous material is the cut-off voltage of the pore having the lowest cut-off.

It may be concluded, therefore, that finely porous materials will have high cut-off voltages.

This is confirmed in the curve of Fig. 8, which shows the cut-off voltage for four porous materials, determined by cathode ray oscillograms. An average pore diameter for these materials was estimated by Mr. B. S. Covell by a determination of the pore volume, and from the rate at which a fluid under pressure flowed through the materials.

In the derivation of the volt-ampere characteristic shown in Fig. 7C it was assumed that the pores were all distinct, and that although they might not be at all straight, they ran more or less parallel paths so that there were no intersections of pores. Hence, the events in the different pores were independent, and the breakdown of one pore would have no influence upon the breakdown of a second pore until the appropriate breakdown voltage of the second pore was reached. This, in general, will not be the case in an actual porous material, for in it the pores cross one another, have portions in common, and constitute a tangled labyrinth of paths. Any particular path which breaks down may intersect or have a portion in common with another path. As a result of this second path having a portion which is carrying a discharge, the breakdown voltage of the second path will be greatly lowered, and it may even fall to a value less than the breakdown voltage of the first path. When this happens the upper branch of the volt-ampere loop

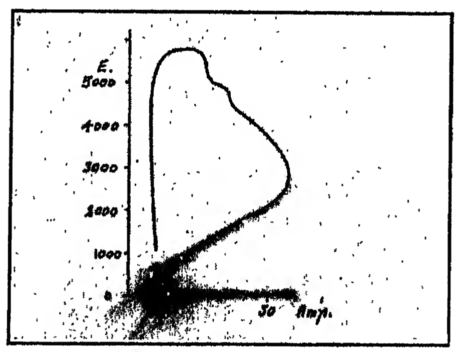

Fig. 9—Discharge through Piece of Brick

may slope downwards instead of upwards. This effect will be most pronounced in coarsely porous materials.

This is well brought out in the cathode ray oscillogram for a discharge through a 6.3 mm. thick piece of brick shown in Fig. 9. The breakdown of some of the pores, so lowered the breakdown voltage of the other pores, that the voltage fell with increasing current. The actual course of the upper branch of the volt-am-

pere loop, when it is falling in this way will now depend on the characteristics of the circuit supplying the current. The lower branch of the volt-ampere loop for this piece of brick is of the nature predicted in Fig. 7C.

IV. Discharges in Slightly Conducting Porous Materials

By confining the discharge following breakdown to very fine channels it is possible as we have seen to raise greatly the minimum voltage for maintaining the discharge, and thus greatly improve the valve effect. To obtain a voltage ratio sufficiently low to make a good valve type lightning arrester, however, calls for a material with pores of an exceedingly great degree of fineness. The authors have found that by incorporating small amounts of conducting material such as lampblack or powdered metal in the porous material the breakdown voltage is considerably reduced while the cut-off voltage is unaffected. In this way it is possible to greatly improve the valve effect, and to reduce the stringency of the requirement as to the fineness of the pores.

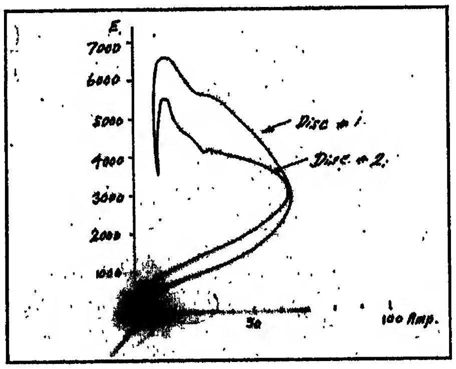

Fig. 10—Discharge through Insulating Porous Disks

Fig. 10, for example, shows cathode ray oscillograms of volt-ampere loops of porous disks 5.0 cm. in diameter and 3.2 mm. thick which were practically free from conducting material so that their resistance when measured at 1000 volts was about 2000 megohms. Fig. 11 shows the characteristics of a similar disk but containing a small amount of carbon so that its resistance when measured at 1000 volts was 30,000 ohms. Comparing the two oscillograms, we see that the addition of the carbon had only a very slight effect upon the lower or cut-off branch of the loop, whereas it greatly lowered the upper or breakdown branch, thus greatly improving the valve effect.

The way in which the finely divided conducting material causes the breakdown voltage to be lowered is readily pictured. The conducting particles are distributed through the porous material, and are too few in number to form many conducting paths through the material. The few continuous chains of conducting particles through the material account for the conductivity at low voltage (30,000 ohms in the disk of Fig. 11).

Besides these continuous chains, there will be some chains of conducting particles which are not completely continuous but have tiny breaks in them. When the voltage impressed on the piece is raised to a few hundred volts those chains which have single tiny breaks will begin to carry current, a discharge occurring across the tiny break in each chain. The current in this discharge is kept small by the high resistance of the fine chain leading up to the break. As the voltage is further raised, chains of conducting particles with two or more breaks begin to carry current. Thus, the porous material becomes permeated with these tiny discharges across the minute breaks in the conducting chains.

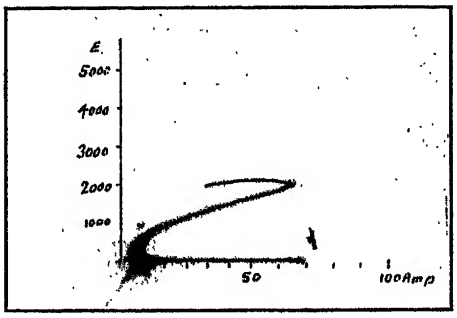

Fig. 11—Discharge through Slightly Conducting Porous Disks

The presence of these tiny pilot discharges will cause the breakdown in the various pores to be lowered very greatly. This is shown in Fig. 7A by the loop $O\ D\ E\ F$. As the voltage is raised from zero there is now a leakage current due to the conducting chains. When the point D is reached enough pilot discharges have formed to cause the fine hole to break down as a whole. The current then increases to the value at point E on the rising part of the volt-ampere curve for a discharge in the hole. If the voltage is now lowered, at C the cut-off voltage for the hole, the current will drop to the leakage value at F. The effect of the addition of conducting material is shown also in the loops $O\ D\ E\ C\ F$ in Figs. 7B and 7C.

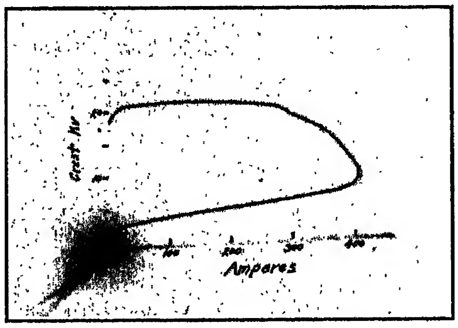

Fig. 12—Discharge through Disk with Eight Per Cent of Aluminum Powder

It will be noticed that the current taken by the hole

at the breakdown voltage is lessened when the conducting material is added. Hence, with a multiplicity of holes in parallel for the discharge of a given current more holes will participate, as is clear from Figs. 7B and 7C. Thus the duty on each hole resulting from the mechanical stress due to the pressure developed by the discharge is lessened since both the voltage and the

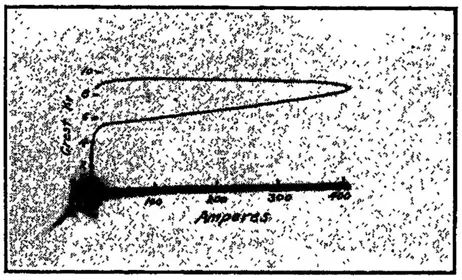

FIG. 13—DISCHARGE THROUGH DISK WITH 12½ PER CENT OF ALUMINUM POWDER

current are lowered. This is a very important advantage obtained by the addition of the conducting material. The tendency to shatter or puncture observed in insulating porous material when subjected to very heavy discharges was almost completely eliminated by the addition of the proper amount of conducting material.

The amount of conducting material added to the porous material must of course be properly chosen if desirable lightning arrester characteristics are to be obtained. If too little is used, the breakdown voltage will be high in comparison with the cut-off voltage, and the material will also tend to shatter or puncture.

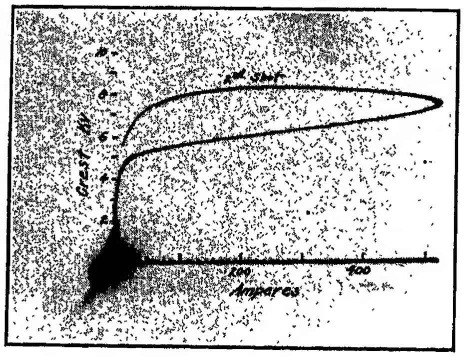

FIG. 14—DISCHARGE THROUGH DISK WITH 20 PER CENT OF ALUMINUM POWDER

If too much is used the large leakage current will cause the cut-off to be vague and impose too great a duty on the series spark-gap.

As an example, the results obtained with a series of disks made of a special clay with varying amounts of aluminum powder may be mentioned. When the aluminum was less than 4 per cent of the weight of the disk, the breakdown voltage was very high, in fact so high that on test the discharge usually passed over the edge of the disk rather than through the pores. With the aluminum weight from 4 per cent to 37 per cent, quite good volt-ampere loops were obtained, with sharp cut-off. When the aluminum content exceeded 37 per cent the leakage current became so great as to quite obliterate the cut-off. Figs. 12, 13, and 14 show the progressive change in volt-ampere characteristics with increasing aluminum content.

CONCLUSIONS

The theory and experimental work described above show that there are good possibilities for the development of a valve type arrester utilizing discharges confined to fine pores of a naturally porous material. In a later paper, the authors hope to show how these possibilities have been realized.

Discussion

Edward Beck: The authors have described a new principle which permits the construction of valve type arresters of a new form. The development of lightning arresters incorporating this new principle has passed out of the theoretical stage. About 3000 arresters of the confined-discharge type have been placed in the field for the purpose of accumulating service experience. The first of these installations was a modest one for 2300-volt service made on August 1, 1928. This was quickly followed by others for the same and higher voltages until both line and station

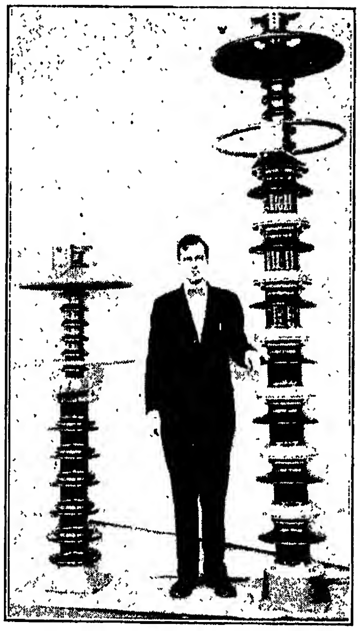

FIG. 1

type arresters have been installed on circuits operating on lines up to and including 110 kv. A 132-kv. station installation will be completed this month.

The standard autovalve arrester was based on the theory that a valve, that is, a voltage-limiting device with a cut-off or valve-closing voltage at the crest value of the arrester's rating, lends itself to the construction of an ideal arrester. The many years of service experience with the autovalve arrester have established the validity of this belief. This valve principle is retained in the new arrester, which might be considered to be born of the

autovalve arrester. However, the performance, although it resembles that of the autovalve, is secured in a radically different manner by the construction worked out by the authors of the paper.

The insulating and supporting structure and series gaps in the new arrester follow the tried and established design of the autovalve.

The reduction in size and weight and the greater convenience of installation which this new arrester principle will permit is indicated by the accompanying illustration. We may look for the day when lightning arresters will be suspended from the towers and station structure, thereby eliminating the space requirement now necessary in the station for lightning arresters.

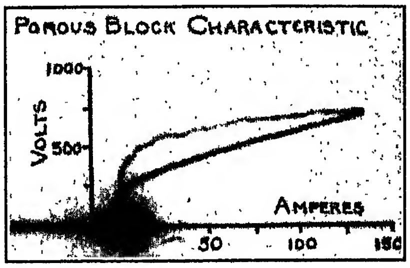

FIG. 2—VOLT-AMPERE CURVE ON 3-INCH DIAMETER DISKS CONTAINING 17 PER CENT ALUMINUM

With over 2500 arrester-years of service experience, the performance of these new arresters has been highly satisfactory, particularly when it is borne in mind that 1929 produced one of the most severe lightning seasons experienced in several years. Equipment and insulator strings protected by the confined discharge arresters have been singularly free from lightning damage and the ruggedness of this arrester principle has been definitely indicated by these field trials.

K. B. McEachron: The authors state that in the autovalve arrester "the discharge is constrained to remain in the form of a glow" . . . which is "distinguished from the arc in that it requires several hundred volts for its maintenance." As I pointed out in my discussion of Dr. Slepian's 1926 A. I. E. E. paper referred to, the autovalve arrester does not maintain a voltage of several hundred volts when the current decreases to small values. In my discussion I showed the first cathode ray oscillograms to be taken on the autovalve arrester showing that at low-current values the potential was less than 100 volts. Using volt-ampere curves given by Atherton in the April 13, 1929 *Electrical World*, a voltage of 170 volts per gap is obtained which included the $I R$ drop in the disks. Just what this resistance drop may represent in volts is not known, but all of the available data which I am familiar with indicate about double the glow voltage at the time of breakdown and about one-half the glow voltage at the time of sealing. This statement applies to disks in contact so that the spacing is small. It would seem therefore that the autovalve arrester uses the glow principle rather more imperfectly than the authors' statement indicates.

The discussion of the use of restricted passages in a lightning arrester structure is very interesting and represents a valuable contribution. This method of obtaining satisfactory arrester operation, *i. e.*, comparatively low breakdown and high sealing voltage, was disclosed by Percy Thomas in U. S. Patent 882,218 issued in 1908. This patent provides for a large number of conducting particles giving a large number of independent discharges in parallel but constructed so that each path would prevent follow current. Porosity is not discussed in the patent but seems to be a necessary characteristic to give desired discharge.

In Figs. 12, 13, and 14 cathode ray oscillograms are shown indicating the effect of increasing the aluminum powder content. The cut-off potential for the 8 per cent powder in Fig. 12 is approximately 2.5 kv. and about 5 kv. for 12½ per cent and for 20 per cent aluminum as shown in Figs. 13 and 14. It would be interesting to know if all of these tests were made on the same size disks and if the aluminum powder was the only variable.

I have been doing some work along the same line as the authors but have not obtained results quite as good as those given in the paper. Fig. 2 herewith, shows the results obtained from a porous structure containing 17 per cent aluminum powder. The tests indicate that the characteristic obtained is due in some measure to contact conditions at the surface of the electrode and porous material. I wonder if the authors have evaluated the contact effect. It would be of interest in this connection to know whether or not the authors have succeeded in maintaining the characteristic in thick sections or if the porous material will have to be kept in the form of thin disks in order that proper performance may be secured.

The tests which I have made indicate a considerable degree of instability, especially at large current values of the order of 1000 amperes or more. Perhaps a better balance between pore size and amount of conducting material will improve the situation.

In general any characteristic depending on the breakdown of air will exhibit time lag. The greater the rate of application of potential the greater will be the breakdown potential. It can be stated as a general rule that any volt-ampere characteristic which shows a loop in which the current decreases at a lower voltage than it increases will indicate a possibility of time lag. The authors' comment on what they have found with regard to the time lag of porous materials will be helpful.

In connection with materials for lightning arresters I shall describe at the Winter convention a resistance material called thyrite, which has been developed in Pittsfield. Thyrite is a true resistance and as shown in Fig. 3 herewith, has a volt-ampere characteristic which shows no loop whatever as its characteristics do not depend on the breakdown of any gas. For a given applied potential a current will flow which does not depend on the previous history of the discharge nor on whether the discharge is large or small. The d-c. resistance at a given potential is exactly equal to the resistance under transient conditions for the same current or potential, even though the transient may rise to its crest in a millionth of a second or less.

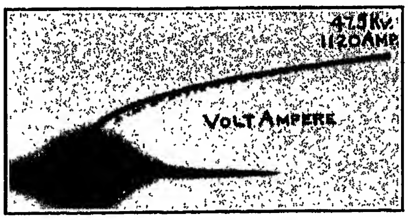

FIG. 3—CHARACTERISTIC VOLT-AMPERE CURVE FOR THYRITE 6-INCH DIAMETER AND 8¼ INCHES HIGH

A. E. Knowlton: The considerable similarity of the new arrester to a string of insulators and the manner of direct attachment to the line conductors and towers makes one wonder what opportunities they provide. Is it permissible to infer that this development is one stride forward to the ultimate aim of making every insulator a lightning arrester?

Joseph Slepian: Mr. McEachron again refers to the lack of perfection of the autovalve arrester in its property of constraining the discharge through it to remain in the form of a glow rather than to take the form of an arc. This lack of perfection is admitted. In fact in the design of the arrester this lack of perfection is the one factor which determines the resistivity to be used in the autovalve disks. In my 1926 paper I say "the resistivity of the electrode material must be made only high

enough to take care of surface in homogeneities and the partial contacts due to bridging particles." Also in my closing discussion to that paper I say, "there is a low-voltage part during the last 50 amperes of the discharge which is undoubtedly due to vague contacts and lining up of particles in the gap by the intense field." These quotations recognize the appearance of agents which cause current to flow at less than glow voltage. Proper design of the arrester is able to reduce the effects of these agents in the arrester, itself, but so far has not been able to affect the important place which they have in Mr. McEachron's discussions.

Mr. McEachron refers to the pioneer work of Percy Thomas described in his U. S. Patent 882,218. The arrester described in this patent apparently did not utilize the properties of discharges confined to very fine pores which are described in this paper. This Thomas arrester was manufactured by the Westinghouse Elec. & Mfg. Co. following the specifications of the patent and sold under the name of type M. P. arrester. The discharge element of this arrester is certainly porous, and when tested at sufficiently high voltage does show the characteristics of a rather poor arrester of the pore-discharge type. The reason for this poor performance is lack of sufficient fineness of the pores, and lack of sufficient uniformity of the fineness of the pores. Neither of these requirements is mentioned in the Thomas patent. The material used was also not suitable mechanically to withstand the effects of repeated discharges in fine pores. To obtain these discharges in the pores of the type M. P. arrester it was necessary to apply voltages many times that of the electric lines for which the arrester was designed. This again shows that complete discharges through the pores were neither contemplated nor obtained. The Thomas arrester undoubtedly depended for its action upon tiny sparks across breaks in chains of conducting particles very much as described in the third and fourth paragraphs of Section IV of the paper presented.

Regarding the comparison of Figs. 12, 13, and 14 with respect to cut-off voltage, the records show that for Fig. 12, due to the high breakdown voltage, there was a partial flashover making the position of the cut-off voltage uncertain. The tests corresponding to the three figures were made with disks of the same size, and so far as possible with the same pore size. To eliminate the effect of imperfect contacts, the faces of the disks were coated with metal by the Shoop spray process.

We have found no particular instability in our porous materials at high currents, although I suppose there is some limiting current at which the material would shatter or be damaged in some way. In the laboratory we send discharges of thousands of amperes through porous blocks with no noticeable change in the material. We have in service 66 arresters of this new type on a short length of 66-kv. line. This line formerly flashed over seven-disk insulator strings quite frequently, so that it is quite safe to say that the arresters are receiving discharges of more than one thousand amperes. So far, no arrester has failed.

I cannot agree with Mr. McEachron that there is any necessary relation between time lag and the area of the loop in the volt-ampere characteristics. The sphere-gap, for example, is generally credited with being the fastest of discharge devices, and for moderate overvoltages, has a time lag of only a fraction of a microsecond. Nevertheless its volt-ampere characteristic has a tremendous loop. Thus, the 1-cm. spark-gap referred to in the paper has a loop which reaches from the breakdown voltage of 30,000 down to the cut-off voltage of 40, and yet if the electrodes are moderately large spheres, this spark-gap will have very little time lag. The time lag of the discharge through porous materials has been found to be very short. Data on this will be given in the future.

The similarity in appearance and size of the new arrester to a string of insulators leads Mr. Knowlton to inquire as to the possibility of replacing insulator strings by arresters. If the mechanical strength of the arrester case can be made sufficiently great, I see no reason why this should not be feasible.

Low-Voltage A-C. Networks
of the Standard Gas and Electric Company's Properties

BY R. M. STANLEY[1] and C. T. SINCLAIR[2]
Fellow, A. I. E. E. Member, A. I. E. E.

Synopsis.—The low-tension a-c. network utilizing secondary network protectors has been adopted by five properties of the Standard Gas and Electric Company for service in areas of high-load density. The system has been applied to cities of the second class and smaller, although load density in certain cases is high. Each individual installation was made after a specific study of conditions involved.

Underlying principles on which all of the designs are based are: (1) Primary supply at generator voltage (11 kv. or 13 kv.), (2) Omission of feeder regulators, (3) Simplified transformer vault design with barrier wall between primary and secondary equipment, (4) High-reactance transformers, usually inherent, (5) Use of secondary network protectors, (6) Three-phase four-wire secondaries, (7) Use of 250,000 cir. mil. secondary mains (or smaller) forming a solid grid without fuses.

The operating experience of the installations made thus far has justified their application. The use of the system in other areas will be considered in future planning.

* * * * *

THE low-tension a-c. network has come into general use for distribution in the medium sized and larger cities. There are two general reasons for this: first, the high standard of service rendered, and second, the economies resulting.

The high standard of service, both from a standpoint of continuity and regulation, is in a broad sense the result of the principle of a secondary grid fed by a number of primary feeders. Primary faults are isolated by automatic switching. Secondary faults clear themselves. Hence, a failure of either portion of the system does not affect the service rendered.

As there is a strong tendency toward higher voltages, the regulation of the primary feeders is usually negligible. The regulation of the secondary grid is good because of the parallel paths and multiple feeds at the intersections of the grid. These principles are well known and have been discussed at length through the medium of the technical press.

The economies resulting from the application of network principles usually lie in the elimination of the substation by utilizing the generation voltage. Saving is further made in substation operating forces. Improvement in system efficiency is often apparent by use of higher distribution voltage and saving in transformer core loss during light load periods.

Great improvements have been made in network equipment in the past few years and failures of switches to operate correctly are now very infrequent. This is strikingly evident from the fact that out of over 34,000 service operations of the switches installed on the Pittsburgh network only 18 or about 0.05 of 1 per cent were not correct. Service was unaffected by these incorrect operations.

Networks of Standard Gas and Electric Properties

Five of the larger properties of the Standard Gas and Electric group have adopted the low-voltage a-c. network for distribution in the business district of the cities served, namely Minneapolis, St. Paul, Oklahoma City, Louisville, and Pittsburgh.

The same general plan is being followed in all of these installations. All are of the three-phase four-wire type serving (with the exception of Minneapolis) both power and light from the same secondary mains. The Minneapolis network has separate power and light mains, resulting from an early development, but is essentially a three-phase four-wire system. All are to be served eventually at generator voltage from the generating station, although in some cases a lower voltage feed from a substation will be used for the first step to utilize an existing primary system, until the load in the district develops sufficiently to warrant replacing it with one at a higher voltage.

Type of Load

The type of load found in the business districts of these cities is typical of that found in larger cities. A number of large office buildings, department stores, etc., are scattered throughout the district, the greater part of which is, however, covered with comparatively small buildings housing small shops.

The power load in these cities is chiefly motors, driving elevators, refrigerating machines, printing presses, etc., and the relation between power and light in the load in each city is as follows:

	Light	Power
Minneapolis	70%	30%
St. Paul	60%	40%
Oklahoma City	60%	40%
Louisville	52%	48%
Pittsburgh	56%	44%

The load densities in these cities is as follows:

Minneapolis	34,000	kv-a.	per	square	mile
St. Paul	52,000	"	"	"	"
Oklahoma City	47,000	"	"	"	"
Louisville	20,000	"	"	"	"
Pittsburgh	90,000	"	"	"	"

1. Byllesby Engr. & Mgt. Corp., Chicago, Ill.
2. Byllesby Engr. & Mgt. Corp., Pittsburgh, Pa.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

In Oklahoma City and St. Paul the areas supplied by networks are at present small, and therefore the load density is higher than might be expected for cities of this class. In Minneapolis and Louisville the areas covered by networks are larger and therefore the load density is lower.

In Pittsburgh, however, where the area supplied by the network is approximately equal to that in Louisville and Minneapolis, the density is very much higher due to the greater development of the district and the larger number of high office buildings, department stores, etc.

The reasons for the adoption of the network were generally the same. The cities had outgrown their old distribution systems and a very considerable expenditure would be required to expand or change them sufficiently to be able to continue to meet the requirements of the rapidly increasing loads. Decision to adopt networks were reached only after careful studies of local conditions, each case being decided entirely upon its own merits.

Design Features

In the design of all the networks certain broad principles were followed. These are as follows:

(a) Primary supply at generator voltage.
(b) Omission of feeder regulators.
(c) Simplified transformer vault design.
(d) High-reactance transformers, usually inherent.
(e) A system with secondary network protectors.
(f) Three-phase four-wire secondaries.
(g) Use of 250,000-cir. mil, secondary mains, and smaller, forming a solid grid without fuses.

(a) Supplying the network at generator voltage from generating stations eliminated substation construction. In certain cases feeders were also run from substations for added flexibility or as an initial step. In other cases use was made of the existing 4-kv. substation capacity for network purposes.

(b) It was decided to omit feeder regulators where possible after an analysis of the system voltage conditions was made. When higher voltages are used for distribution the primary voltage drop is usually not a limiting factor, except where very long cable runs are necessary. Where the network supply voltage can be varied throughout the day feeder regulators may be omitted, especially if the primary cable runs are relatively short.

(c) A simplified vault design has been developed with a material reduction in the amount of cable work required and a fireproof barrier wall separating the primary and secondary equipment. This design is described in detail later in this paper.

(d) Transformers with 10 per cent reactance are generally used. This reactance is preferably made inherent. Subsequently in the paper a discussion of the value of this transformer design will appear.

(e) The system utilizing network protectors was adopted because of the increased measure of protection afforded to the low-voltage network and to service from the network, since this protective device is nearest to the network. By its use segregation of potential trouble in transformer vaults, in transformers themselves, in primary and secondary connections in transformer vaults is accomplished.

(f) The three-phase four-wire secondary offers a universal system whereby power and lighting loads can be served from the same secondary mains. There have been some objections to 199 for power voltage, but these have been met by the use of boosters when difficult situations were encountered.

(g) Relatively small secondary mains, 250,000-cir. mil and smaller, were adopted as a result of cable burning tests which indicated that larger cables were more difficult to clear in event of a secondary fault. When required, two sets of mains can be installed each in a separate duct. This, of course, requires an additional duct, but these ducts are frequently available because of the elimination of numerous cables on systems being replaced. Secondary grids are not fused and expensive servicing of fuses eliminated and cost of fuse boxes saved.

Information on the important features of the networks is given in Table I. Further details on some of the points are given in the following paragraphs under the headings of the different cities.

Minneapolis

Formerly, Minneapolis transformers with isolated secondaries were supplied by 4-kv. looped feeders. When the secondaries of these transformers were interconnected to form a network, it was decided to supply additional transformers to be connected to this network by 13-kv. radial feeders. This decision was made as a result of an extensive study of the relative costs and merits of 4-kv. and 13-kv. systems, which showed that the cost of 13-kv. radial feeders for a load increase of 12,000 kv-a. would represent a considerable saving when compared with the cost of 4-kv. feeders and 13/4-kv. substations. Fig. 1 shows the Minneapolis network area.

The Minneapolis network has a number of distinctive features. It is the only one of the group which does not supply both power and light loads from the same secondary mains and which is fed by both 13.8- and 4-kv. banks in parallel. At the present time there are 17 of the former and 23 of the latter. The reactance of the 13.8-kv. transformers is 5 per cent and that of the 4-kv. 3½ per cent. External reactors are installed in the secondary circuit. Some trouble has been experienced during low load periods when the secondary voltage supplied from the 4-kv. systems is higher than that supplied from the 13-kv. system, resulting in some of the network protectors opening and shifting load on the secondary cables.

The 4-kv. bus at Clinton Substation which feeds the 4-kv. network feeders is regulated and corrects for

TABLE I
GENERAL CHARACTERISTICS OF STANDARD GAS & ELECTRIC NETWORKS

Subject	Minneapolis	St. Paul	Oklahoma Gas & Electric Co.	Louisville Gas & Electric Co.	Duquesne Light Co.
Area of network present, sq. mi.	0.57	0.125	0.10	0.50	0.50
Present load in network area, kv-a.	19,300	6,500	4,700	10,000	45,000
Kv-a. per sq. mi.	34,000	52,000	47,000	20,000	90,000
Load on network, end of 1929, kv-a.	9,100	1,500	5,800	2,300	22,000
Percentage light and power	Light 70 Power 30	Light 60 Power 40	Light 60 Power 40	Light 52 Power 48	Light 56 Power 44
Number of transformer banks	13.2 kv. 3 ϕ—16 13.2 kv. 1 ϕ— 1 4 kv. 1 ϕ—23	4 kv. 1 ϕ—20	13.2 kv. 3 ϕ— 9 13.2 kv. 1 ϕ—21	13.2 kv. 3 ϕ—16	11 kv. 3 ϕ—102 11 kv. 1 ϕ— 43 4 kv. 1 ϕ— 43
Ratio installed capacity to peak load	2 to 1	3 to 1	1.6 to 1	2.04 to 1	2.68 to 1
Primary voltage	13,200 4,000	13,200 4,000	13,200	13,200	11,000 4,000
Number of primary feeders	2 at 13.2 kv. 2 at 4 kv.	3	3	2	7 at 11 kv. 8 at 4 kv.
Source of supply	2 substa.	2 substa.	1 substa.	Gen. sta.	11 kv. gen. sta. 4 kv. 2 substa.
Feeder regulators	None	Regulators[1]	None	None	None
Secondary voltage[2]	Lt. 115/199 Pr. 230[2]	120/208	120/208	115/199	115/199
Secondary grid	Fused	Sectionalized by fuses[3]	Solid	Solid	Solid
Transformer sizes kv-a.					
13.2 kv. 3 ϕ	500 & 300	....	300	300 & 500	....
13.2 kv. 1 ϕ	150	....	100	....	....
11.0 kv. 3 ϕ	....	....	....	....	500
11.0 kv. 1 ϕ	....	....	....	....	100
2.4 kv. 1 ϕ	200, 150, 100	100	....	....	100
Voltage rating of transformers	13,800–120/208 2,400–120	2,400–120	13,800–120/208	13,200–115/199	11,500–120/208 2,400–120
Transformer impedance	5% inherent + 5% external reactance shunted by fuse	4% inherent	10% inherent	10% inherent	10% inherent on 11 kv 4% inherent + 6% external reactance on 4 kv.

Notes:—
1—Three single-phase regulators on each feeder; compensators not interconnected. These regulators were in use on the old radial system.
2—All secondaries are three-phase, four-wire except the power secondary in Minneapolis which is three-phase, three-wire connected through auto-transformers.
3—To be operated with sectionalizing fuses until sufficient short-circuit current is available to make the fuses unnecessary.

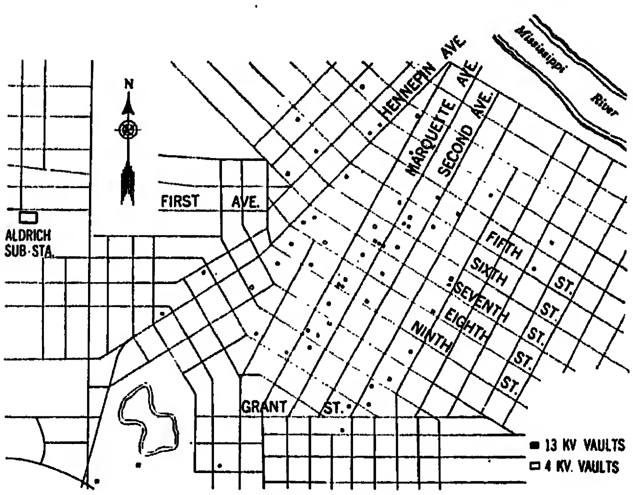

FIG. 1—MINNEAPOLIS NETWORK AREA

variation in system voltage only. The regulators are blocked in one position depending upon the load and voltage so that the load will divide properly between the 4-kv. and 13.8-kv. banks.

The secondary grid is of 500,000 cir. mil. paper insulated lead covered cables. Three-conductor cables were used on the initial step, but single conductor 250,000 cir. mil has now been adopted as standard.

Open type network protectors are used and line type transformers on the 4-kv. system. The 13.8-kv. transformers are the subway type.

All 13-kv. vaults have a fire wall between the transformer and network protector. Some of the 4-kv. vaults have an asbestos board enclosure around the transformers, but others have no separation.

St. Paul

The St. Paul area is shown in Fig. 2.

Prior to 1929 the a-c. distribution system in this section consisted of a number of radial feeders (some at 2.3 kv. and others at 4 kv.) supplying a comparatively large number of small capacity transformer vaults. Emergency primary service was provided by bringing two feeders into each vault. Each vault supplied its

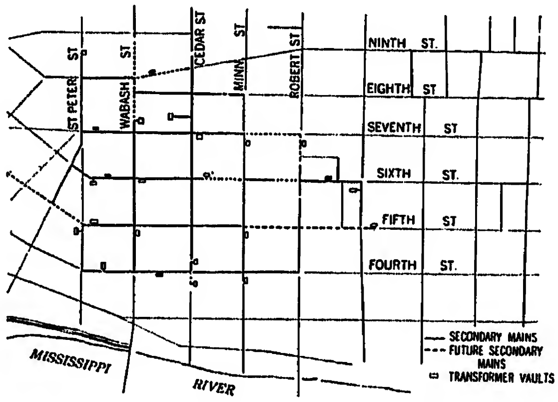

Fig. 2—St. Paul Network Area

own definite load and no provision was made for emergency service in case of failure of a transformer or a secondary cable.

With the rapid increase in the demand for a-c. service in this section it had become evident that some radical changes in the system must soon be made to provide more reliable service for the downtown buildings. Among other things it was certain that larger capacity vaults must be built, and that they must be provided with entrances accessible at all times. The existing vaults were nearly all located in the basements of buildings and were accessible only through the buildings, which often resulted in delays in gaining entrance. These requirements led to the decision to replace a number of small vaults with a few larger capacity vaults, each located under a sidewalk, independent and isolated from adjacent buildings and accessible through hatchways placed in the sidewalk.

Furthermore, the primary system was not uniform. With the exception of the downtown district the old 2.3-kv. system had been eliminated and the 4-kv. system had been substituted.

A study indicated that since rebuilding was necessary, the secondary network offered the most economical and satisfactory solution.

Another factor influencing this decision was the fact that very satisfactory progress had been made during past few years in substituting a-c. service for d-c. service in the downtown district. It is expected that with the reliable service which a secondary network is capable of providing, the reduction in the total d-c. demand will be sufficient to warrant the elimination of certain conversion equipment when it reaches the end of its useful life.

While the initial network step is supplied by 4-kv. primaries, the ultimate design calls for 13-kv. primary supply. The secondary grid is of 250,000-cir. mil single conductor cable, although some 500,000-cir. mil cable is used. Due to the low values of short circuit current obtaining on the initial step, the secondaries are sectionalized by fuses. This is a temporary measure.

The later vaults conform to the newer principles of design in using the barrier wall design.

Oklahoma City

In Oklahoma City, until the adoption of the network, the distribution system was entirely overhead. When it was decided to place the system underground, the network was adopted as being best suited to local conditions and the type of system most easily expanded to meet increased loads.

The Oklahoma City network, Fig. 3, utilizes single conductor 2/0 primary street mains. It is supplied by three primary feeders from a regulated bus at the Broadway Substation. Individual feeder regulators are not used.

The majority of vaults have a single compartment in which both primary and secondary equipment is installed. The later vaults, however, have been designed with a barrier wall and all future installations will follow this design.

A bank of three single-phase units was installed in the first vaults to be built, but three-phase units are

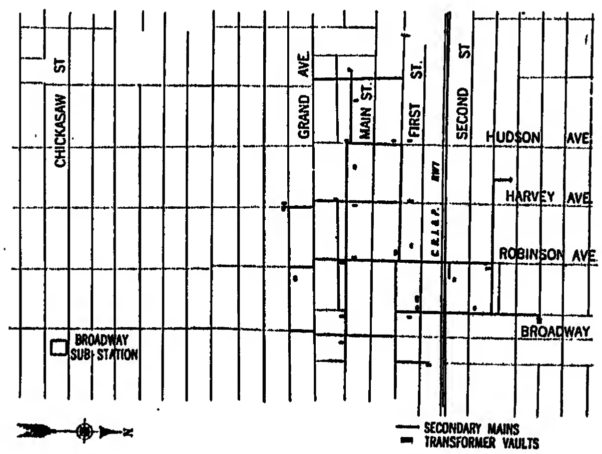

Fig. 3—Oklahoma City Network Area

being used in the later installations. The transformers are subway type with 10 per cent inherent reactance wound for a 13,800-volt delta connected primary, and a 120/208-volt star secondary. The primary winding has four 2½ per cent taps below normal. A primary grounding and disconnecting switch is provided inside the tank of the single-phase units. The three-phase units have external grounding and disconnecting switches in the high-voltage terminal chamber.

Network switches are of the subway type, and 1200-ampere capacity. There are 10 of the solenoid type, and 20 motor operated, 15 of the latter having trip free mechanism.

Braided cable is used between the transformer and network switch on the newer installations, although the older jobs were made with lead covered cable.

Both primary and secondary cables if lead covered, are supported on cable racks with an insulator between the sheath and the rack. The braided cable is supported by porcelain cleats.

The secondary grid is formed of single conductor 500,000-cir. mil lead covered paper insulated cable. Three cables and a 500,000-cir. mil bare neutral are installed in one duct. They are not fireproofed in either the vault or the manhole.

Boosters are installed for power loads, when required. Not more than 1 per cent of the 220-volt load has required auto-transformers. As there are no very high buildings in the city, no serious elevator problems have arisen.

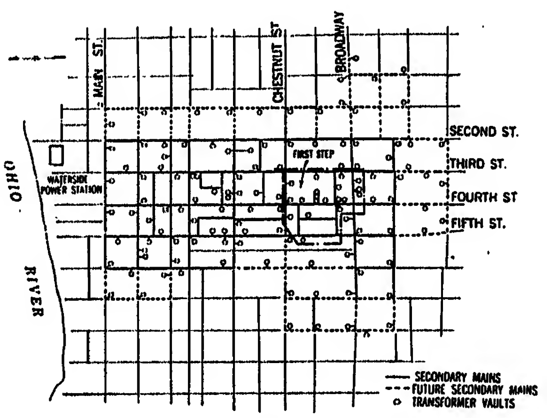

FIG. 4—LOUISVILLE NETWORK AREA

LOUISVILLE

In Louisville the principal business district is centered about the intersection of Fourth Street and Broadway, and covers an area about one-third of a square mile in extent. Fig. 4 shows the business district with respect to the Waterside Generating Station on the Ohio River. About two years ago it became evident that a limit had been reached in the expansion of the distribution system designed several years before to serve this section. A radical change in the system was required. As a result, a detailed engineering study was made of the situation, considering a number of possible methods of serving the section. These included a 4-kv. radial system fed in one case from the Waterside Generating Station, and in another from a new downtown substation, a 13-kv. radial system from Waterside, a 4-kv. low-voltage a-c. network fed in one case from Waterside and in another from a downtown substation, the extension of the existing system, and a 13-kv. network fed from Waterside. The relative costs of the system studied are of interest.

	Type of system	Relative cost based on three 5-yr. construction programs including carrying charges
1.	4-kv. radial from existing substation...	1.10
2.	4-kv. radial from new substation (disconnecting switch transfer).........	1.34
3.	Same as 2 except (oil switch transfer)..	1.41
4.	13-kv. radial from generating station..	1.86
5.	4-kv. network from substation (same as 1)............................	1.23
6.	4-kv. network from new substation (same as 2) disconnect transfer......	1.40
7.	Same as 6 except oil switch transfer....	1.44
8.	13-kv. network with 250,000 cir. mil (sec. mains)........................	1.00

By disconnect transfer is meant that the station was designed for transferring the circuits from one bus to the other by disconnecting switches. The alternate was by oil switch transfer.

The study is based upon detailed estimates of each system in its entirety. It was assumed that an increase to 30,000 kv-a. in load could be expected over a fifteen-year period. Losses and operators salaries are included in addition to the actual cost of the money.

It was found that a low-voltage a-c. network fed at generator voltage from Waterside would be the most economical system in the ratio shown. The system closest in cost is 10 per cent higher and was not considered comparable with the network from a standpoint of reliability of service, ease of operation, expansion, and feasibility of construction in the streets.

The secondary system of the Louisville installation is three-phase four-wire 115/199 volts. The general network plan covers an area of a little more than half a square mile, although the initial step covers a somewhat smaller area. The primary supply is at 13 kv. directly from the Waterside Generating Station. The transformers are 300 kv-a. with 10 per cent inherent impedance, in barrier vaults described later. The secondary mains are 250,000 cir. mil although existing mains of smaller size are used where possible. No regulators are used in the primary feeders.

The cutover was accomplished by the construction of a small number of vaults forming a small network. The load was then cut over to this network and new vaults added gradually.

PITTSBURGH

The business district of Pittsburgh lies between the Allegheny and Monongahela Rivers immediately at their confluence. The area covered is one-half square mile but is triangular. Fig. 5 shows this area with respect to the rivers, and Fig. 6 shows the detail of the business district. The two principal generating stations, Colfax and Brunot Island, are shown and the 66-kv. ring bus connecting them.

Before the installation of the network, the business district in Pittsburgh, Fig. 6 was fed by 4-kv. three-phase radial feeders from three substations located near the three corners of the district. Duplicate throw-over service, necessarily involving an interruption, was supplied to most of the customers by feeders from different substations from which they were normally fed. In addition to the 4-kv. system many customers were still

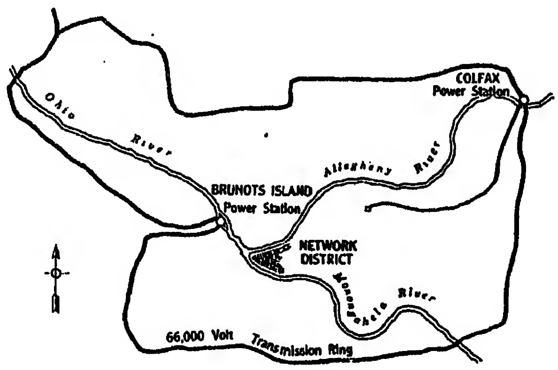

Fig. 5—Showing Relative Location of Network and Sources of Supply

served from the remnants of older systems eventually to be discontinued. These included one-, two-, and three-phase, 2300-volt systems and a small d-c. radial system. No d-c. network was ever installed in Pittsburgh.

The downtown substations were fed primarily by 11-kv. feeders from the Brunot Island Generating Station located on the Ohio River about three miles downstream. Another generating station at Colfax about fifteen miles up the Allegheny River is tied to the Brunot Island station through a 66-kv. transmission ring around the city. A few 22-kv. feeders from ring substations also fed into the downtown substations.

In 1926 the 4-kv. equipment in the downtown substations was loaded to its safe capacity. A number of large buildings was planned for immediate construction about this time, which indicated a considerable increase in new business load in addition to the normal growth in the existing load. A very considerable increase in 11-kv. and 4-kv. substation (Stanwix) equipment would have been required to serve this additional load satisfactorily. This major extension of the substation would have meant additional transformer capacity with necessary bus extensions and oil circuit breaker equipment. The cost of such an extension would have been large. Further expenditures would have been required for additions to the 4-kv. distribution system. Duplication of services in the downtown section had caused such congestion in the duct lines that new duct construction was necessary unless concerted effort was made to clear existing ducts.

Studies of cost of service in the Triangle were made as follows: first, extending existing 4-kv. radial system; second, a-c. network fed at generator voltage direct from Brunot Island Generating Station.

The results of these studies indicated clearly that a very considerable saving would result from the adoption of the network fed from the generating station with a material improvement in service to customers. It was also found that by taking all of the load over on to a network the number of old cables removed would be greater than the number of new cables required, with a net gain in spare ducts, making new duct construction unnecessary.

Secondary Voltage. A three-phase four-wire network operating at 115/199 volts and fed by a large number of comparatively high reactance banks was adopted for the Pittsburgh District.

The lighting voltage had been standardized in Pittsburgh at 115 volts and most of the motors in use were of the 220-volt type. A star connected system with 115 volts to neutral would be satisfactory for lighting but would supply only 199 volts for the motors. This is, however, within the 10 per cent low limit guaranteed by the manufacturers for satisfactory motor operation.

The Six-Section Plan. The network is divided into six sections as shown in Fig. 7. One 4-kv. section is fed by four feeders from Stanwix Substation, one 4-kv. section fed by four feeders from Grant Substation, and four 11-kv. sections fed by four feeders from Brunot Island, one from Stanwix Substation, one from Grant Substation, and one from 13th Street Substation. The 11-kv. sections take in more than four-fifths of the networked area. Each section will be served by three

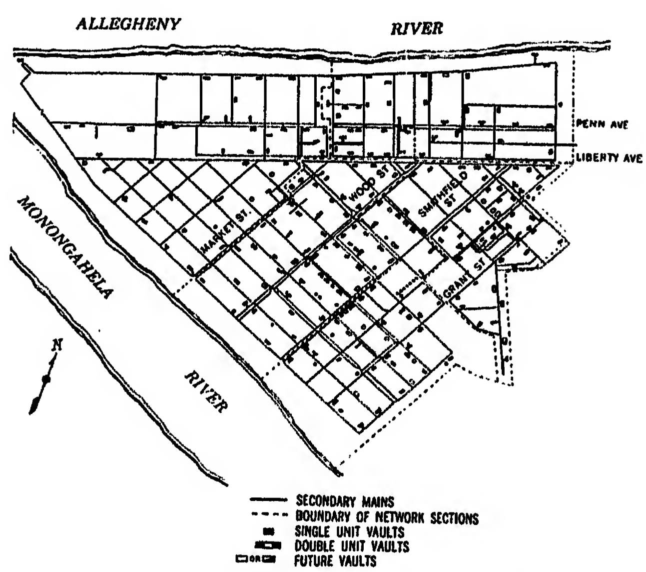

Fig. 6—Pittsburgh Network Area

feeders. This is the smallest number that it is thought safe to install. Any one of these feeders may be taken out of service and held out indefinitely without overloading the other two. It was decided that no one feeder should serve more than two sections. The minimum number of feeders required to satisfy these conditions (*i. e.*, 4 sections, 2 sections to a feeder, 3 feeders to a section) is six. Actually seven have been installed,

but the seventh, an existing 4/0 cable from 13th Street, is required only for added flexibility. It is used for the fourth transformer bank in a few large customers' installations. Without this feeder two of the banks in these vaults would have to be fed from the same feeder.

The feeders have been arranged in such a manner that any one of the four sections may be completely de-energized by disconnecting the three cables feeding it

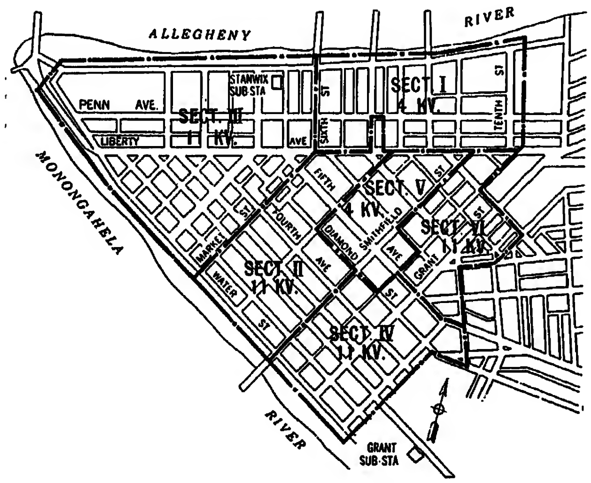

Fig. 7—Map Showing Six Sections of Pittsburgh Network

without affecting more than one cable in any other section. Thus with a minimum of six cables it is possible to de-energize any three and still have two left to carry the load in each of the three other sections. The remaining cables will not be overloaded.

A total of 190 banks of 300-kv-a. transformer capacity will supply the district upon the completion of the 1929 construction program. Approximately two-thirds of these are to be 11-kv. units. The majority of these are in single-unit vaults, but there is quite a number of vaults with two and some with three and four units.

Primary System. The 4-kv. primary feeders consist of 3-conductor 500,000-cir. mil sector shape copper, paper insulated lead covered cables. Primary mains consisting in some cases of the same size cable and in others of 250,000 cir. mil depending upon the number of vaults to be connected, radiate from the feeders. The feeders operate in parallel from the same bus at the substation.

The 11-kv. primary feeders consist of 3-conductor, 500,000-cir. mil sector shape copper, paper insulated lead covered cables.

The 11-kv. mains from the feeder are either 3-conductor, 500,000-cir. mil or 3-conductor, 4/0 cable, depending upon the number of vaults to be served.

Floods. An unusual characteristic in Pittsburgh, which must be taken into consideration in the design of an underground system, is the frequency with which serious floods occur. A rise in the river of 20 ft. above the normal stage is not unusual, and a rise of 15 ft. is sufficient to flood basements in the Triangle. Drains are, of course, useless at such times and pumps are of value only in retarding the rise of water in the basements. The flood stage takes in about one-half of the area of the Triangle. All electrical equipment installed underground within this portion must be of the submersible type. The vaults are consequently designed to operate indefinitely when completely filled with water.

Transformer Vault Design. The single-unit vaults consist of two compartments, usually without a connecting door. The transformer is located in one compartment and the network switch and other secondary equipment in the other. This design is shown in Fig. 8. Access to each compartment is generally through a separate opening in the sidewalk. Where permits for two openings cannot be obtained, a fireproof door is provided in the dividing wall. This door is hung so as to swing into the closed position when not forcibly held open. The wall between the vault and the basement of the adjacent building is solid without any opening. This design resulted from property damage on customers premises on occasion of vault fires. Openings in the wall between compartments are located 14 in. or more above the floor, and where a door is necessary a sill 14 in. high is built across it, or of sufficient height to hold all of the oil of the transformers in the enclosed space in case of bursted or leaky tanks. The average floor space required for a single unit vault is approximately 64 sq. ft. for a three-phase, and 88

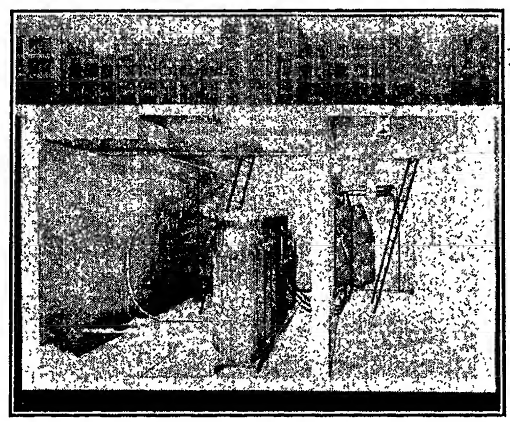

Fig. 8—Low-Voltage A-C. Network Vault

sq. ft. for single-phase primary compartment, and 40 sq. ft. for the secondary compartment. The minimum headroom is 10 ft., providing sufficient headroom for future 500 kv-a. transformers. Transformer banks are placed in individual primary compartments of reinforced concrete where more than one bank is used, thus isolating each bank. One installation recently placed in service contained seven banks. There are numerous others in service with 2, 3, and 4 units. Network switches for such installations are placed to-

gether in a single secondary compartment. Designs are available for isolation of secondary units should future operating experience indicate that this is desirable.

Ventilation for the primary compartment is normally by natural draft. Forced draft is provided in a few instances. The secondary compartment is not ventilated unless a booster is installed. With natural ventilation the inlet and outlet are placed in the side-

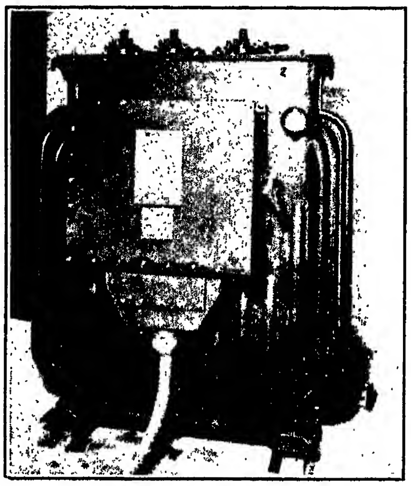

FIG. 8A—DETAIL OF STANDARD VAULT—LOUISVILLE

Primary cable terminating in pot head at base of oil immersed disconnecting switch on transformer. Operating handle for disconnecting switch is shown on right side of switch box

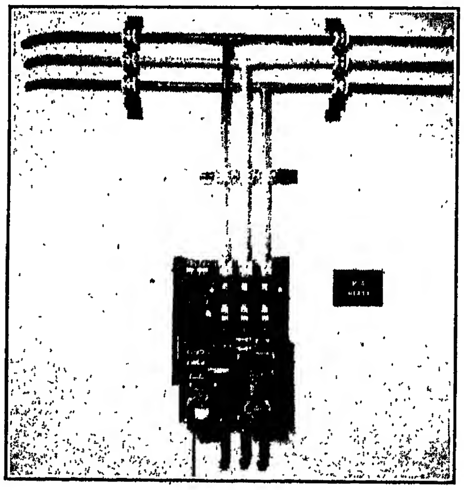

FIG. 8B—DETAIL OF STANDARD VAULT DESIGN—LOUISVILLE

Secondary bus construction with line type network protector. Flame proof cable used for bus work. Note cables from lower side of network switch running through barrier wall into primary compartment

walk near the building line and covered with sidewalk type gratings. Usually an opening of 4 sq. ft. is obtained. An all metal trap door is provided below each grating, normally held open by a fusible link. In case of fire producing sufficient heat to melt the fuse the door will be closed by a counterweight and prevent flames rising through the grating to the street.

Cable work was reduced to a minimum, especially the secondary work. Primary cable runs from the duct entrance in the wall directly to the pothead which is an integral part of the transformer. It has been common standard practise in the past in secondary runs to use lead covered cables for subway type construction between the transformer and network switch with a wiped joint at the transformer. Recognizing that it might be difficult to burn off a fault occurring between

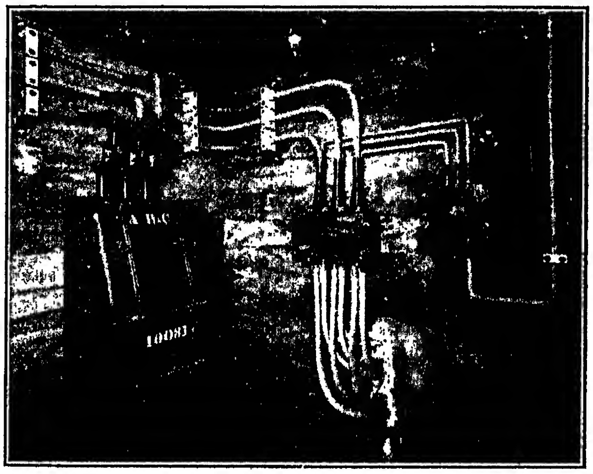

FIG. 8C—DETAIL OF STANDARD VAULT—PITTSBURGH

Subway type network protector with bus and fuse box. Flame proof cable used throughout. Note fire proofed secondary lead covered cable from fuse box into ducts

FIG. 8D—RIG USED IN LOWERING TRANSFORMER INTO VAULT—LOUISVILLE

phases where 1,000,000-cir. mil or larger cable is used, it was decided to reduce this hazard materially by using a varnished cambric flame-proof cable with the shortest possible run.

Stud type porcelain bushings are used on the transformer secondary. These bushings are water-tight and provide a ready means of terminating the transformer

secondary and at the same time preventing leakage of water into the transformer when submerged. The same type bushing is used on the network protector. The transformer and network protector are thus submersible, and are protected against water seepage through the strands of the flame-proof cable.

The flame-proof cable is continued from the outgoing side of the network protector and terminates in a water-tight fused junction box. Lead cables from the street connect at this point to the wiping bushings. The junction box provides a convenient means of connecting the flame-proof cable to the lead covered cables, providing a water-tight terminal. Vault lighting is supplied through a similar but smaller junction box.

Transformers. The 100-kv-a. single-phase subway type transformers previously used in the 4-kv. radial system have been transferred to the 4-kv. network. These transformers have approximately 3.8 per cent impedance and external reactors (cable type, built up of iron punchings) are used to bring the total reactance up to about 10 per cent.

New transformers selected for the 11-kv. network are three-phase, 300-kv-a. units and single-phase, 100-kv-a. units provided with four 2½ per cent taps below normal on the primary side. The inherent reactance of these transformers is 10 per cent. The value of 10 per cent reactance was adopted as a compromise value which would afford the best voltage regulation possible, together with an economical spacing of transformers required to provide sufficient short circuit current to burn off secondary faults, while at the same time providing against overheating or damaging of any one or more transformer banks during a burning off process following secondary network cable breakdowns.

Potheads for the primary cables and a primary grounding switch are mounted in a sheet steel box attached to the case of the transformers. The lead sheath of the cable is wiped to a sleeve on the bottom of this box. No cable joints are therefore required between the manholes and the transformer. A completely water-tight job that can be safely installed in flooded areas is thus obtained. The primary switch is used only for convenience in taking a unit out of service for maintenance or repairs, and cannot be operated while alive. It is mounted in such a manner as to be readily accessible upon removal of a bolted cover. It is electrically interlocked in such a manner that it cannot be opened while the transformer is energized. The operating mechanism is so arranged that it is necessary to close the switch in the transformer position before moving it from the open to the ground position. If the line is energized it will then energize the transformer and cause the electrical interlock to engage, thus making it necessary to de-energize the line before the switch can be operated.

Network Protectors. The earliest type of network protector is a solenoid operated carbon circuit breaker controlled by three single-phase relays. The second is of the motor operated contactor type controlled by one master polyphase relay and with a phasing relay which is designed to prevent pumping under exceptional conditions such as when the transformer voltage lags the network voltage.

The latest type is similar to the last but has a trip free mechanism. All future switches installed on the system will be of this type. Switches generally used are rated at 1200 amperes.

Secondary System. Cables used in the secondary system are 250,000-cir. mil lead covered single-conductor with 4/0 bare neutral. The three cables and neutral are installed in one duct. When required, more capacity is obtained by an additional set of mains in a separate duct. In such cases they are paralleled at street intersections. The secondary system and transformer vaults are shown in Fig. 6.

The secondary cables are not fireproofed. Sheath currents are allowed to flow, and due to the low mutual reactance and the comparatively high resistance of the sheath circuit, the currents are not of sufficient magnitude to cause appreciable heating.

Fuses. All customer's services fed directly from a transformer vault and connections between the transformer banks and the street secondary mains are fused. Customers' services fed from the secondary grid are not fused in the street, but a fused entrance switch adjacent to the cable terminal is supplied by each customer. In the sectionalizing scheme each of the six areas is covered with a solid grid isolated from the others. No fuses or junction boxes are used to sectionalize the secondary grid.

Boosters. Boosters are required on services feeding two-wire, 220-volt heating elements as 199 volts is too low for satisfactory operation. It is found that nearly all motors will operate satisfactorily at 199 volts. Boosters are, however, installed for motor services where a higher voltage is desirable. The cost of boosters amounts to only a small percentage of the total cost of a standard installation, and their use does not appreciably affect the cost of service from the network.

Procedure during Cutover of Load. Previous to the adoption of the network the smaller loads in the downtown area were fed from distribution vaults each supplied with two 4-kv. feeders. In the case of the first 4-kv. network, it was possible to install network equipment in nine of these vaults by shifting load from one to the other and rebuilding one at a time. Upon the completion of this work the secondaries from these vaults were tied together. Three feeders supplied the nine transformer banks, three banks from each feeder. The network protectors were locked closed forming a non-automatic network. As it required only a few hours to make the secondary ties, the hazard from primary cable trouble was not great. The network

switches were then made automatic putting the network into operation.

New vaults were added one at a time until all vaults in the area were tied into the network.

The conditions were somewhat different in cutting in the second area. There were several 4-kv. radial vaults which were to be eliminated and 11-kv. supply substituted. A small network was formed by connecting the secondaries of the four 4-kv. vaults. Nine 11-kv. vaults had been constructed in the area and the transformers energized, the network switches being locked open. The secondaries from the 11-kv. transformers were next connected to the small 4-kv. network. Upon the completion of these ties, the network switches in the 11-kv. vaults were closed paralleling the 11-kv. and 4-kv. systems. The 4-kv. transformer banks were then disconnected transferring the load to the 11-kv. supply without interruption to service. The remaining 4-kv. vaults were transferred by paralleling their secondaries and disconnecting the vaults one at a time.

The entire process of cutover presented no difficult problem as the 11-kv. and 4-kv. systems were designed for parallel operation when required. Such changes were usually made on Sunday during the light load period.

Secondary Faults. A most important consideration in the operating of an a-c. network is to be certain that secondary faults will clear before any serious injury has been caused to the system as a whole. With a solid grid such as that installed in Pittsburgh, secondary faults must burn clear as no other means has been provided for isolating them. The great majority of faults will clear themselves with very little effect on the remainder of the system. In some extreme cases, however, the fault may hold on for some time and produce a considerable amount of smoke and fire which if it does not cause any damage probably will be objectionable from a public-relations standpoint. To guard against these possibilities it is necessary to make certain that the short circuit current that will flow into a fault at any point in the system is sufficient to clear it under the most exacting conditions in a very short time. The short circuit current is determined by the impedance of the primary cables, the number of transformer banks feeding into the grid, their proximity to the point at which the fault occurs, and the impedance of the grid. Generally the proximity of the banks to the fault is the determining factor. To insure the safety of the system at the time of a secondary fault, it is therefore necessary to properly proportion the size of copper used to the number of transformer banks available. In a few cases, it is necessary to install banks which are not required for load conditions, but are required to increase the short circuit current available at the time of a fault. The magnitude of the short circuit current required varies with the size of conductor used for the secondary grid. The Duquesne Light Company has adopted a 250,000-cir. mil conductor for this purpose. Certain 500,000-cir. mil cable is used in a few localities where sufficient short circuit current is available to clear it in a minimum of time.

Types of Faults. There are two general classes of faults that may occur on the secondary grid, grounds between conductor and sheath, and phase to phase short circuits involving two or three conductors. They may also be classified as point or surface contact faults, a point contact fault being produced when a sharp point like a pick breaks through the sheath and touches one or more conductors, and a surface contact fault resulting when a live conductor comes into contact with a metal pipe or when two conductors from which the insulation may have been burned come into contact with some metal support.

Point contacts are by far the most common of all cable faults, and generally clear almost instantaneously by either fusing the lead around the entering point when only one conductor is involved or by fusing the point when two conductors are involved. Faults of the second type, although comparatively rare, are frequently very serious. These are the faults that must be considered when a system is designed.

Short Circuit Tests. Before adopting the 250,000-cir. mil cable for the secondary mains the Duquesne Light Company ran a series of tests to determine the size copper best suited to the conditions obtaining on the Pittsburgh network, and also to determine the magnitude of the short circuit current required to clear the most serious faults. The test equipment was arranged to simulate conditions that might be actually met, and provide currents as high as 25,000 amperes for long periods. The conclusions reached as a result of these tests confirmed various assumptions which were generally accepted, but for which supporting data were lacking. These may be enumerated as follows:—(1) any size copper will clear if sufficient current is available; (2) the amount of disturbance produced is directly proportional to the size of conductor and the amount of insulation involved; (3) the current required to fuse a given size conductor is considerably less than that determined by Preece's formula,[3] due to the thermal resistance of the cable insulation and duct.

As a result of these tests the 250,000-cir. mil cable was adopted, since 3500 amperes was found sufficient to clear immediately and with little disturbance any fault occurring on this size of cable. The Duquesne Light Company system is accordingly being designed to supply as near as possible 3500 amperes short circuit capacity at all points in the grid. In those localities where 500,000-cir. mil cable is used 6000 amperes short circuit current is provided.

A summary of the test results will be found in the Appendix to this paper.

Paralleling Feeders from Different Sources of Power.

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3. $$I = .\, a \sqrt{d^3}$$

wherein I = current required to fuse conductor, a = a constant depending upon the material, and d = diameter of the wire.

No operating difficulty has resulted from paralleling feeders from a substation with those from the generating station, although there is some unbalance in loading. At the present time the loading of the network feeders is normally less than the loading of those feeding into the downtown substations. The same size cable is used for each purpose. The voltage drop from the generating station to the substation is consequently greater than from the generating station to the network. This amounts to low voltage on the substation network feeders and results in their not carrying their full share of the load. This condition will tend to correct itself as more load is cut over to the network, as this will tend to bring the loading on the substation and network feeders more nearly together and equalize the voltage drops.

Voltage Fluctuations. In order to minimize voltage fluctuations, all large induction motor installations are required to be equipped with a starter preferably of the resistance type that will limit the starting current to increments of 200 amperes at half-second intervals. Other types of starters are permitted if the increments by which the current increases during the starting period do not exceed 200 amperes. The 200-ampere increment will normally keep the voltage dip below two volts even with the poor power factor in starting. In certain cases this limit has been materially extended.

Pumping of Network Switches. Trouble may result from serving one section of a network from two different sources if they should get out of synchronism. At such times the network might be the only tie between them. A heavy cross-current would then flow which might injure secondary equipment and also would reverse the direction of power in one feeder. The network switches on this feeder would then open. This would re-establish normal conditions on the network. The phasing relay would prevent the switches on the out-of-phase feeder from closing if there is sufficient phase displacement. If there is a small difference in frequency, of the order of one or two cycles, opening and closing of the switch might continue for some time and the switch contacts be seriously damaged by the heavy current interrupted. Such trouble is most likely to occur at low load periods, as the network load has a stabilizing effect and tends to counteract the effect of the synchronizing current. A switch not trip-free might in these circumstances be severely burned, therefore trip-free switches are used.

Voltage Regulation. The 4-kv. radial system superseded by the network was served by feeders from a regulated substation bus. The network feeders are not regulated, and voltage tests made from time to time since the installation of the network indicate that regulators are not needed. The generating station bus voltage is, however, lowered at night according to a definite schedule, and this prevents any appreciable increase in the customer's secondary voltage. The permissible voltage regulation on the Pittsburgh network is plus or minus 5 per cent for lighting, and plus or minus 10 per cent for power. The normal network regulation, however, is less than 2 per cent.

Network Switch Operation. The operating of the network switches has been very satisfactory. There has been a total of 34,100 switch operations since the first section of the network was energized. During this time, there have been fifteen primary faults and so far as is known eight secondary faults. Only once did a switch fail to operate on a primary fault. In this instance, the switch blocked and the fuses blew. A total of 18 failures of switches to operate has been recorded. The switches are inspected and tested once a month or oftener in case of any unusual operating condition. Complete inspection and adjustment is made every six months. Periodic load and voltage checks are also made on each bank.

Conclusions

A-c. networks are desirable for the following reasons:

(a) Lower cost of serving the district. Network installations have been found to cost from 80 per cent to as low as 50 per cent of the cost of other systems, effecting a saving in yearly fixed charges.

(b) Economies of operation. These economies result from the use of a higher transmission voltage and a reduction of distribution losses. An important item in reducing these losses lies in the possibility of disconnecting feeders with their transformers during light load periods.

(c) Elimination of operation costs in substations.

(d) Elimination of maintenance costs in substations.

(e) The network is capable of almost indefinite expansion within a given area, or extension beyond to include greater area. Other radial a-c. systems such as throw-over or pick-up schemes soon reach a state of development where it is not possible to foresee clearly how the ultimate load can be satisfactorily served. This has been found to be due in part to street congestion, whereas the study of the network system for such a situation showed ample space for ducts, manholes, and vaults for the ultimate load possible to predict (based upon present experience and method of estimating load).

(f) Reliability of service. Operating experience of several years by other companies has demonstrated that reliability of service and close voltage regulation can be obtained at lower cost with a-c. networks. These experiences have been duplicated on the properties described above, and as further experiences are obtained it may be confidently expected that standardization of method of design will result in further economies of construction and operation and permit giving better service at still lower costs.

Appendix

Secondary Fault Tests. From previous tests it had been found that faults between the lead sheath and a conductor will clear in a few cycles and without seri-

ously injuring adjacent cables. Also, that copper to copper faults formed by loosely wrapping with binding wire or by large (3/8 in. square) spikes being driven into the conductors, will clear in a short interval and will not transmit trouble to the adjacent cables. As a conclusion to the previous tests, it was expected that wherever a fault occurred such as driving a drill into a live cable or where the insulation had become charred and the conductors were allowed to come in contact, that the arc established at such a contact would be sufficient to cause the immediate fusing of the copper and that the fault would be cleared in a very short interval providing sufficient current was available.

It has been questionable, in the rare cases where the conductors come solidly in contact and there is no chance for an arc to be established, whether or not the conductors will burn themselves clear, and if so, what value of current will be necessary. In previous tests such faults could not be cleared due to the thermal

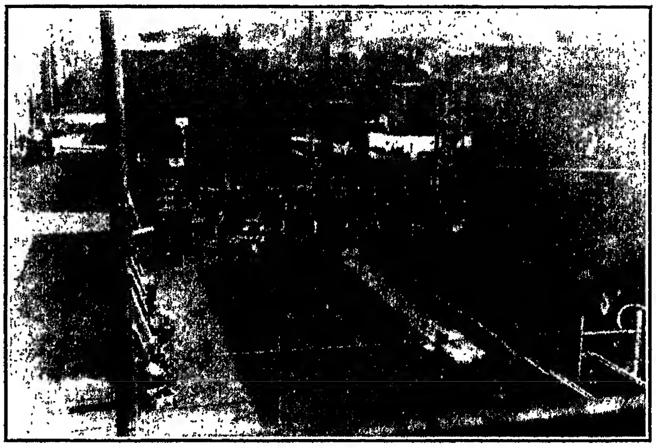

Fig. 9—Test Set-Up Showing Location of Transformers and Duct Line. The Reactors were Wound on the Three Cable Reels at the Transformers

capacity of the test equipment not being sufficient to sustain the current for a long enough period. It was decided to make a set-up of test equipment so that currents from 5000 to 25,000 amperes could be maintained for at least an hour.

Test Set. Ten 300 kv-a., three-phase, 11,000/200-volt network transformers were connected in parallel fed by a 500,000- cir. mil cable directly to Brunot Island generating station. The maximum short circuit of each transformer is approximately 14,000 amperes on the 115/200-volt side so that neglecting the impedance of the bus tie between banks, a possible current of over 100,000 could be delivered. In order to control this value of current a set of reactors was constructed which limited the current in steps from 5000 to 40,000 amperes and these values of currents could be maintained for some time without endangering the transformers or primary cables. The test set-up is shown in Fig. 9.

The cable to be tested was run through a duct line built especially for the tests and consisted of two 4½-in. iron pipes, one 3-in. iron pipe, four 4½-in. fiber ducts, and two 3½-in. fiber ducts all incased in concrete, with a brick manhole at each end in which the joints were made. One end of the test cable was connected with three sets of 500,000-cir. mil cable and the other end with two sets of 500,000-cir. mil cable and all connected to the transformers through a 2,000,000-cir. mil bus.

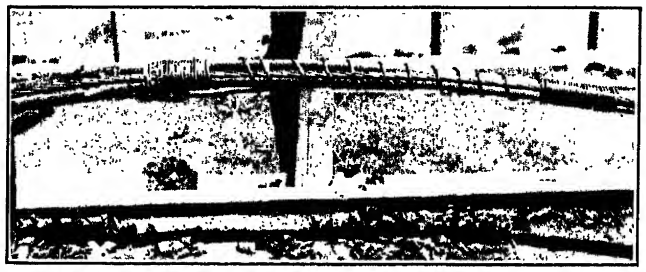

Fig. 10—Type of Short Circuit Employed in the Tests

Note the three conductors and neutral bound solidly together with heavy binding wire

Test Procedure. In each case a short was applied as illustrated in Fig. 10, and the set of cables pulled into the duct and connected up with standard joints and sleeves as shown in Fig. 11. The transformers were then energized by closing the 11,000-volt test breaker and held on for ten minutes after the fault had cleared. After a few seconds smoke and gases began pouring out of the manhole, followed by ignition of the liberated gases as the cables were clearing, the gases and compound from the cables caught fire, and dense clouds of smoke poured out of the manholes. In order to pre-

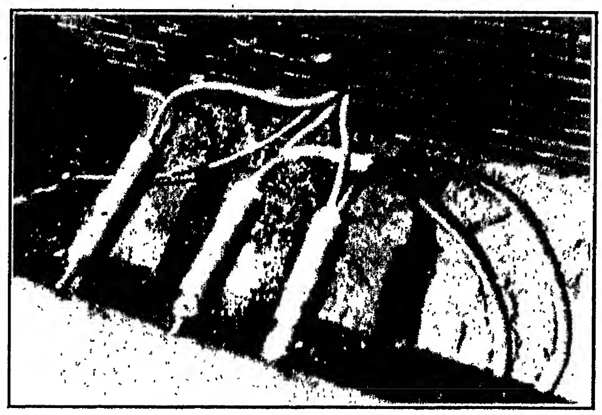

Fig. 11—Standard Joints used in Test

serve the damaged cables the flames were extinguished immediately after the fault cleared.

The metering equipment consisted of large ratio current transformers registering on indicating and high-speed graphic ammeters. An oscillograph was used for a few of the tests but due to the duration of the test, it was not possible to record the clearing of the fault. The value of current shown is the total current and is divided as follows: For 500,000 cir. mil supplied by 3-way feed 67 per cent, by 2-way 33 per cent. For 250,000

cir. mil supplied by 3-way feed 62 per cent, by 2-way 38 per cent. This resulted in one end clearing first and is shown on the charts by the sudden decrease in value. However, the times considered in the test results represents the average total time to clear all phases from both ends, and are therefore based on the total fault current.

The conditions under which each test was conducted and the average time to clear all phases are shown in Table II.

mil cable 67 per cent and 33 per cent). The two-way feed with a three-way junction point at one end and a two-way junction point at the other, was used to simulate actual network conditions. This is diagrammatically shown in Fig. 16.

Ignition of the generated gases was noticed on each test, particularly when the sealed joints blew open.

Joints were made up using copper connectors and by wrapping the leads with binding wire and then soldering.

TABLE II
SUMMARY OF TEST RESULTS

Size cable	Type cable	Duct	Total current	Type fault	Special condition	Time to clear
500 MCM	1 cond.	Fiber	6,000	Sheath to conductor		Few cycles
500 MCM	1 cond.	Fiber	15,000	Solid		172 sec.
500 MCM	1 cond.	Fiber	15,000	Solid		143 sec.
500 MCM	3 cond.	Iron	15,000	Solid		129 sec.
500 MCM	1 cond.	Fiber	19,000	Solid		90 sec.
500 MCM	1 cond.	Iron	25,000	Solid	Mhs. filled with CO_2 gas	45 sec.
350 MCM	1 cond.	Iron	15,000	Solid		78 sec.
250 MCM	1 cond.	Fiber	15,000	Solid		42 sec.
250 MCM	1 cond.	Fiber	15,000	Solid		41 sec.
250 MCM	1 cond.	Fiber	25,000	Solid	Mhs. submerged with water	16 sec.
4/0	3 cond.	Iron	15,000	Solid		29 sec.
1/0	1 cond.	Fiber	15,000	Solid		11 sec.
1/0	1 cond.	Iron	19,000	Solid		8 sec.
1/0	1 cond.	Fiber	25,000	Solid		4½ sec.
No. 6	1 cond.	Fiber	15,000	Solid		3½ sec.
1000 MCM	1 cond.	Iron	6,000	Sheath to conductor		Few cycles

Note: More than 70 tests were made, the above being typical results showing the range.

Tests Results. After each test cable length was examined, as well as all the joints, and their condition recorded. In all cases the fault was cleared by burning off the cable in the manholes between the duct edge and the joint. Fig. 12 shows the same three single-conductor 250,000-cir. mil cables as in Fig. 11, after approximately 15,000 amperes had been passed into the fault.

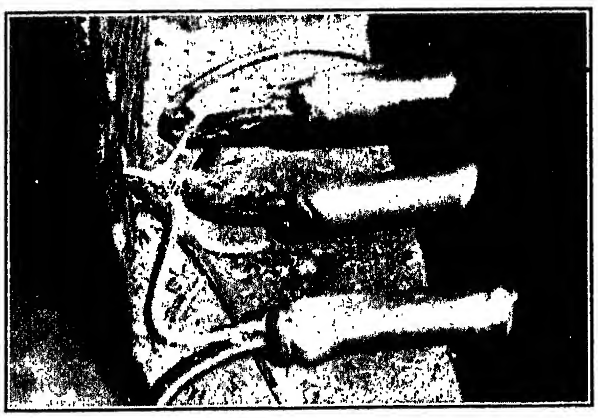

FIG. 12—JOINTS OF FIG. 11 AFTER TEST

Note the clearing of the fault at the joint

The time required to burn the various sizes of cable tested at different values of current is plotted in Fig. 13.

In interpreting the curves it should be noted that the current given is the total current from two directions, the proportionate current values are as previously given (for 250,000-cir. mil cable 62 per cent from one direction and 38 per cent from the other; for 500,000-cir. mil cable 67 per cent and 33 per cent).

One of the joints shown in Fig. 12 is shown opened up in Fig. 14.

One interesting result of the tests shows that when single conductor cables are used the lead will, in most cases, be melted off from the cables in the duct run, but

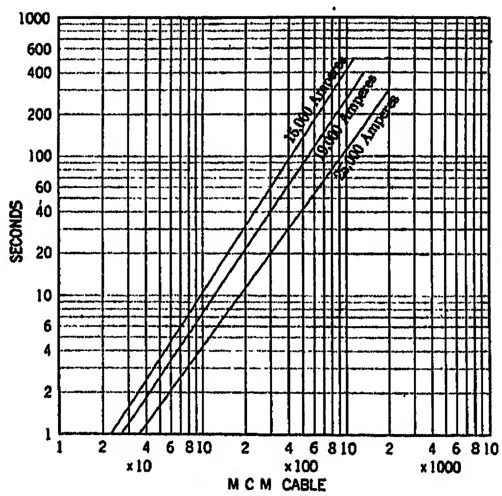

FIG. 13—THESE CURVES SHOW THE TOTAL CURRENT FLOWING INTO THE VAULT FROM BOTH DIRECTIONS AND THE TIME IN WHICH DIFFERENT SIZE CABLES CLEARED

Note that the current is the total of a two-way feed approximately 60 per cent supplied from one end and 40 per cent from the other

that when three conductor cables are used the lead sheath will remain substantially intact, although the insulation is entirely burnt away and the conductors are in contact with the lead. This would tend to show that the actual burning of the lead on single conductor

cables is due in part, at least, to the sheath currents which are produced.

When the fault was cleared under water the volume of smoke was less and there was no evidence of fire. Fig. 15 shows the joints after this test.

In the last two tests a tank of CO_2 gas was liberated in each manhole through a nozzle prior to energizing the fault. The clearing of the fault was identical to the other tests with 500,000-cir. mil cable as far as time and method of clearing was concerned. The smoke which poured out of the manholes during these tests

FIG. 14—JOINTS OF FIGS. 11 AND 12 OPENED AFTER TEST

was as much in volume as in other tests, although the force of the explosions was not as severe and no flames were present. Further tests along these lines might produce interesting results.

Analysis of Test Results. Generally speaking it was found that, where arcs are eliminated by making solid copper to copper faults, the cable has characteristics similar to a fuse. The current-time characteristics

FIG. 15—JOINTS AFTER SUBMERSION TEST

discussed elsewhere, indicate this parallel. There is reason to believe, therefore, that any size cable in common use can be burned off and cleared if sufficient current is available. There is a practical limitation, however, in so far as the volume of smoke or flame liberated is concerned. It is generally agreed that the larger the cable the greater the current and time required to burn clear, and the more smoke and flame will be liberated. There is also a greater possibility of manhole explosion.

Another important consideration lies in the possible damage to the electrical system itself. A study of the effect of secondary shorts as far back as the primary cable indicates that the primary cables themselves and the transformers must be designed to withstand short circuit for a considerably longer period. Tests on the network switch indicate that it is adequate and superior thermally and mechanically to the transformer and secondary cables in a normal system. However, both transformer and switch are protected by a fuse which should be so chosen as to fail first.

The secondary system as a whole should suffer no damage as a result of a fault. Damage to all cable which carries the maximum current is to be expected; but when a two-or three-way feed point is passed (and this should be at the first street intersection) the cable will be found undamaged. This condition is illustrated in Fig. 16.

With a two-way feed to the fault the current in the conductors supplying the faulty section is ½ and the thermal effect is ¼ of that in the faulty conductor. With a three-way feed the current is ⅓ and the thermal effect is 1/9 of that in the faulty section. The test

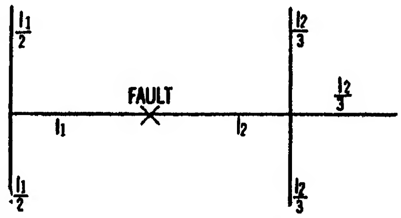

FIG. 16—A NETWORK WITH UNIFORM CABLE SECTIONS AND TRANSFORMER CAPACITIES IS ASSUMED

setup simulated the above condition and many tests on a set of cables forming the two-way and the three-way feed did not materially injure them after completely destroying a number of cables under test carrying the full fault current. We may, therefore, expect the faulty cable to clear at the fault or between the fault and the first multiple feed joint on each side of the fault.

This fact was borne out by the tests since the five sets of cables feeding the faulty cable were used throughout all the tests and the insulation was still in good condition and well impregnated.

Conclusion from Tests. 1. A 500,000-cir. mil cable in either iron or fiber pipe can be burned clear with currents of 5000 amperes and above, and 250,000-cir. mil cable with 3500 amperes and above.

2. The resultant explosion, flame, and violence of burning clear a fault on cables larger than 250,000-cir. mils is so severe as to be extremely objectionable from an operating point of view in a congested business district with narrow streets.

3. With a single conductor cable installed alone in a fiber duct there is no apparent limitation to the size of the copper that can be safely used. The clearing of the fault in this case is not accompanied by explosion or violence but is practically instantaneous due to the rapid fusing of the lead sheath.

4. In general, faults such as conductor to sheath, conductor to conductor, established by means of a pick, drill, etc., are very easily cleared at the point of fault due to contact fusing. In faults, where the conductors become solidly connected, the conductor may not be burned clear at this point but will fuse back often as far as the first manhole, destroying the insulation and lead until physical separation permits it to clear.

5. It was also noted that in a severe type fault there is no difference in the time of clearing a fault with a given amount of current, whether single- or three-conductor cable, and whether it is in an iron or fiber pipe. Faults also were cleared when the manholes were entirely submerged.

6. The resulting flame and explosion can be minimized by the introduction of CO_2 gas in manholes adjacent to the fault.

7. A certain relation between current, time, and conductor size has been established so that it is possible to predetermine with reasonable accuracy what will happen under existing conditions of solid faults.

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Discussion

D. K. Blake: This paper practically completes the descriptive literature on a-c. network systems now in existence and having been in operation for one year or longer. There are a few points that I believe it is worth while to emphasize.

Some engineers hestitate to adopt the network system because they question the reliability of the network protector. Now this paper describes systems having two or three different types made by two different manufacturers, and their testimony is that it is reliable and their testimony is in line with others. So regardless of who makes them there are available reliable network protectors, so it is not a factor in hindering anyone in adopting this system. The real reason why you want an a-c. network system is that the load is growing fast. There is a number of networks on Manhattan Island, and according to the United Electric Light and Power Company, the load density for one of their networks was as low as 1000 kw. per sq. mi. The highest density at that time was about 12,000 kw. per sq. mi. That refers to the a-c. network density, not the d-c. They have found that the low voltage a-c. network system is the most economical way known to take care of the load growth. Because of the rapidity of that growth they are able to start a network with densities as low as 1000 kw. per sq. in. Across the river where there are different conditions, namely spotty concentrations of load, the a-c. network is also chosen.

What makes the network system more economical? It is the use of the high voltage, and that is more economical, because it eliminates the substation.

The question of burning off the secondary cables needs to be seriously considered. I believe this is the first set of tests that really show anything of the ability to burn off cables. I agree with the authors' conclusions. It behooves anyone who is designing a network system to consider the use of the 250,000-circular mil cable instead of the 500,000 circular mil cable. There is not much difference in cost and the difference in reliability involved justifies that little difference.

I believe the authors intended their recommendations of the trip-free mechanism to be confined to the motor centrifugal mechanism which is due to the slowing down of this mechanism after it is de-energized. On solenoid type devices that does not apply. On station breakers we require trip-free mechanism because of the fact that the closing circuit can be energized at the same time as the tripping circuit but in the network protector, the solenoid type or the motor type, the relay has a double-throw contact and it is impossible for both circuits to be energized at the same time. The only reason for requiring a trip-free feature on the motor is because of the time required for the centrifugal weights to stop.

Henry Richter: There are now 47 different properties operating or installing the network system with automatic network protectors, four being in foreign countries. The application is also being studied for at least 26 additional cities, four of which are foreign. The network cities are now located in all sections of the country and range in size from New York down to populations of 40,000. Although in many of them the network was chosen because best adapted to rapidly growing loads, continuity of service, economy, simplicity, etc., have been deciding factors in others. This system is well on its way towards becoming the standard for underground distribution.

The table of total annual charges in the Louisville study shows the network with 4 kv. feeders to be from 2 to 12 per cent more expensive than the radial system, depending on the type of substation. In similar studies for other cities at about the same average load density, but using 500,000-cir. mil secondary mains, the network system with 4000-volt feeders has shown a definite though small saving. One cannot help but wonder whether the difference is due to the extra cost of two 250,000-cir. mil mains in two ducts over one 500,000-cir. mil main in one duct. Not a little of the spread of the automatic a-c. network system has been because of its being more economical.

It is unquestionably true that when the generation voltage is used for the network feeders the greater part of the economy lies in eliminating the substation and its operating force, but savings of 8 to 10 per cent have also been shown for well designed network systems even with the substation in the picture. Furthermore, both of these statements apply only against preceding a-c. systems, as huge economies are shown for any type of a-c. network over direct current.

The omission of regulating equipment when the network supply voltage can be varied throughout the day is in line with the policy to derive from the network scheme as much simplification as feasible, but there are many cities in which it cannot be practised. Data on 29 systems including the five cited in the paper show that in 10 per cent of them synchronous condensers are employed, in 7 per cent bus regulators, in 52 per cent feeder regulators, and in 31 per cent nothing. A comparison in terms of transformer capacity connected to the feeders gives percentages of 4, 2, 67, and 27. If the question arises as to how much past practise on existing feeders of the 4-kv. class may have influenced those figures, a check of the transformer capacity fed at 11-kv. and higher shows the division to run 2, 2, 56, and 40.

The high ratios of installed transformer capacity to peak load listed in Table I are temporary, it will be observed, and will hardly be approached when all of the present load in the network area has been cut over to the network.

Several years ago the United Electric Light and Power Company in New York introduced the idea of incorporating a feeder grounding switch with the network transformer, the switch being a safety measure. Shortly afterwards a further advance was made in the Pittsburgh system by the addition of means for disconnecting the transformer, the three-position switch then being put in the high-voltage terminal chamber rather than inside the tank. Not only has it the advantage mentioned in the paper but it is of value when starting network operation with only two or three feeders, for by disconnecting a transformer on which work is to be done the need of taking out of service all the capacity connected to the feeder can be avoided. It can also be used for

breaking the connection between transformers and feeder if a kenotron test on the cable is desired without building the transformers to stand the test.

For three single-phase transformers the Pittsburgh manholes are stated to be about 25 per cent larger in total volume than for one three-phase transformer. This illustrates the outstanding advantage of three-phase network transformers. Other appreciable benefits are:

Lower cost of transformers at about 300 kv-a. and up.

Lower total losses in most instances.

Fewer bushings and cable connections.

A single three-pole three-position switch is cheaper and simpler than three two-pole three-position switches.

Less maintenance.

Only one unit to handle in stocking and installation.

Manhole arrangement simpler than where there is need to pass one transformer by the others to install or remove.

This noteworthy innovation, first used for underground networks in the United States on the Pittsburgh system two years ago, has been adopted by 17 other companies besides the Standard Gas and Electric properties. This makes a total of about half of all network systems operating or being installed. There are now at least 350 of these transformers in use.

Transformers with 10 per cent inherent impedance at full load have practically the same value under short circuit current. When network load densities reach the neighborhood of 100,000 kv-a. per sq. mi., calculations show the possibility of secondary fault currents as high as 50,000 amperes. One probability is that such a current would burn the most severe fault clear so quickly that the disruptive and heating effects due to the magnitude would not be harmful. Another is that a dangerous condition might result. To take reasonable steps to avoid this possibility appears to be sound engineering, and to this end the transformer with 10 per cent impedance by inherent design is justified.

As for limiting the current through the transformer to prevent damage during the burning off of a secondary cable fault, experience with normal impedance transformers shows that no such trouble results if the protector back-up fuse current rating is not over three times that of the transformers.

At the relatively lower load densities encountered in the average network system, the more the current at a secondary fault the more quickly will the latter be cleared and the less the likelihood of the trouble spreading. As external reactors to increase the bank impedance to a total of 10 per cent saturate under short circuit current, the use of normal impedance transformers assists in furnishing the desired high fault current on these average systems. The smaller the network the more is this true.

It has been a decided advantage in some networks not to have the extra reactance in fixed form as in the inherent design arrangement. For example, when operation is started with 4000-volt feeders and 13,000-volt feeders are introduced into the same network later, the extra reactance at the 4-kv. banks is removed if the total impedance at the 13-kv. banks is to be 10 per cent; this is to offset the impedance of the 4-kv. substation transformers.

Again, in building vaults it was customary to connect the building services and street grid to the transformers as in Fig. 1 herewith. When the help normally obtainable from the street mesh is relatively low and the power factor of a service not high, the voltage regulation can be improved by rearranging as shown in Fig. 2, without sacrificing the advantages of the extra reactance.

Furthermore, changing conditions as the network grew have made changes in the total impedance at all banks advisable in some cities.

The obvious advantages of obtaining the additional impedance by inherent design must therefore be balanced against the flexibility of the external reactors. Of a total of 29 network systems on which the facts are available, three-fourths have normal impedance transformers, mostly with external reactors, and the other quarter use 10 per cent inherent impedance. Classifying these groups by approximate transformer capacity now installed, the division stands 82 per cent against 18 per cent.

The excellent record of the network protectors reported in the paper, added to similar expressions from many other sources, comes as a boon to those interests who at the start invested heavily in money and effort on the possibility that this system

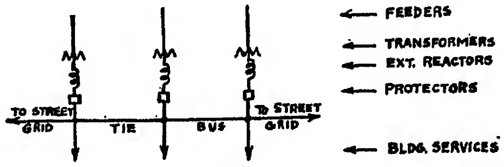

FIG. 1

would spread, and ever since have been striving to help make such statements come true. This should answer the question in the minds of those engineers who have held off, waiting for the protectors to be perfected.

There is a reference to troublesome tripping of protectors in Minneapolis on the 4-kv. feeders at light load. These feeders having individual regulators, it is very probable that their voltage can easily be lowered enough during this period to prevent any tripping whatever.

Non-lead-sheath cable for the large-size connections usually run between network transformer and subway type protector, and between the latter and the secondary mesh, was started in Pittsburgh and is somewhat startling in wet manholes. Considerable experience in service indicates the application to be entirely successful. The idea is rapidly spreading to other cities besides the Standard Gas and Electric group.

Some claim that these lengths of cable constitute so small a part of the total low-voltage cable in a network system that the possibility of a serious fault on them may be discounted. On the other hand, as this extra precaution against trouble costs no more and requires but little change in the transformers and protectors, it appears to be a distinct step forward. Its success depends, of course, on the seal at the porcelain bushings really keeping the water out. One type of seal is a gasket. A superior method is the soldered seal on porcelain, originally developed for mercury arc rectifiers and since extended to potheads, insulating rings in cable splicing sleeves for suppressing sheath currents, etc. This joint is now tested at the factory with hot oil under 80 lb. per sq. in. pressure.

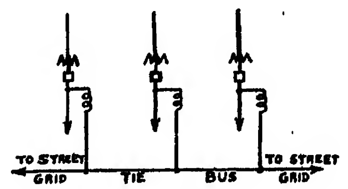

FIG. 2

The secondary junction box in the protector compartment is one way of making connection between the flame proof cable from the protector and the lead-covered cable from the mesh, but is just another piece of apparatus to maintain. Experience on both d-c. and a-c. networks also shows that such boxes are unnecessary for sectionalizing purposes, so it would be advantageous to find some way of dispensing with them. It is possible to connect the lead-covered cables directly to the non-lead sheath cable and to ensure a watertight joint by care in taping. If better assurance is desired some form of soldered-seal-on-porce-

lain connection can be applied. By arranging the joints as close to the ceiling as possible the likelihood of water getting at them is reduced to a minimum. This method facilitates the measuring of current in the mesh cables by a split core transformer without error due to sheath currents, and permits of easily adding more cable connections.

It is difficult to see the value of the fuses between the transformers bank and street secondary mains, for the zinc back-up fuses in the network protectors are provided for the very same purpose.

While the simplified vault arrangement derived by using a three-phase transformer is an asset both in lower cost and easier operation, in some cities the firewall, with its extra manhole opening or fire door, is considered an added complication. In one of the first automatic network systems provision was made for firewalls if found necessary but none have been put in thus far. A severe explosion once occurred in a manhole transformer but the protector, located on the opposite wall, cut the bank off from the network instantly and the trouble did not spread.

The principle of ample manhole ventilation adopted for these properties is an excellent example to follow. So is the use of porcelain saddles under lead-covered cables on racking arms. There is a number of systems where their omission, in combination with other adverse circumstances, may be an invitation to trouble.

From Fig. 7 it appears that most of the six sections into which the secondary grid has been divided in Pittsburgh are so small that considerable advantage in diversity between transformer banks and secondary mains is sacrificed. Much more spare transformer and feeder capacity is also required for a three-feeder network than a six-feeder network in providing against one's being out of service. Considerable experience in other cities shows no need for this precaution if the network is properly operated. There is even some question whether dividing the network into a number of small grids may not sacrifice some reliability as regards outage of feeders, there being a total of six feeders to rely on if the grids are merged into one, against only three feeders for each small network.

In a few cities where 250,000-cir. mil mains as inherited from the radial system are on both sides of almost all streets, it was natural for this size to be continued for new loads. In many cities, however, the mains were 500,000 cir. mils, particularly where confined to one side of the street and there is a desire to continue with this size in the network.

Two 250,000-cir. mil mains in two ducts are more expensive than one 500,000-cir. mil main in one duct. It is true that the cost of duct space for the second duct need not be included if enough ducts are available for the period of comparison, usually 10 years; but frequently new duct banks must be constructed immediately or in a few years and the cost of the duct therefore cannot be omitted. Where the network results in big savings, as by eliminating substations or in displacing a d-c. system, this extra expense for the smaller size mains may be readily absorbed. It may be an important factor, however, when the margin in favor of the automatic network is not large.

Exterpolating on the curves in Fig. 13, it appears that 6000 amperes on a 500,000-cir. mil fault of the most severe type requires about 8 minutes to clear. If this is found to be within the borders of permissible (though not desirable) time for Pittsburgh conditions, and it is admitted that such faults are quite rare, many engineers will be unwilling to go to extra expense to do better than this.

Should it be thought advisable to limit the amount of flame and smoke further, but to retain the simplicity rendered by the 500,000-cir. mil size, cutting the time in half would probably give satisfactory results. This is largely a question of furnishing enough current. According to the curves it could be accomplished with about 10,000 amperes. In areas of such high load density as in Pittsburgh the fault currents will far exceed this value except possibly around the edges and while the network is in the initial stages of construction. In the average network system that can economically employ 500,000 cir. mil mains 10,000 amperes will be obtained over the greater part of the system if the transformers are of normal impedance.

Wherever this current is not available in the normal design of the system the transformer capacity can be increased to make it certain. The authors describe an instance in which this was done, even though the capacity added was not required by the immediate load. The extra capacity is usually not long idle. Where the lack of current might give rise to too much disturbance but it is desired to limit the expense to prevent this, the method of confining the remedy to only those portions of the network in which the deficiency of current would exist is offered as an alternative to the use of 250,000 cir. mil secondary mains throughout.

S. M. Hamill: The Cincinnati company which I represent has had an a-c. network in operation for about two and one-half years. This network is supplied with three 13,000-volt feeders from the generating station. The secondary mains are three-phase four-wire, only one set of mains being used, 120 volts for lighting and 208 for power work. Mr. Blake mentioned the reliability of the network protectors. This has been shown to us by the fact that we have had three feeder faults and in each of these cases the feeders cleared practically instantaneously with no resulting disturbance to the system. Inasmuch as the authors have touched on the maintenance of their network system, I should like to mention its inspection.

In addition to the regular inspections in the vaults themselves the Union Gas & Electric Company daily checks the operation of the network protectors from the generating station supplying the 13.2-kv. feeders. This is done in the early morning light load period by opening one at a time the feeder oil circuit breakers. If the protectors of the opened feeder are all in good operating condition they will open immediately on reverse excitation current. The generating station operator determines this by noting the pilot light of the potential transformer connected to the feeder. In case one or more protectors fail to open, the pilot light does not go out. The feeder is then left de-energized from the generating station until a check is made to determine what protector remains closed. This check can be made very rapidly as there are red and green position-indicating lamps mounted in the vaults where they may be seen from the sidewalk through the grating, so that the patrolman does not have to get out of his automobile to check what feeder failed to open. This has been of some use because in each of the three primary feeder faults which I mentioned, on the day before, one of the network protectors failed to open when the test was made.

H. W. Eales: I should like to mention that the low-voltage d-c. system on Manhattan Island has now reached the staggering proportions of 400,000 kw. In the face of that load, and in the face of a rapid continuing growth in the load and especially a growth in the very heavy density reaching the order of 100,000 kw. to the sq. mi. as contrasted with some figures mentioned by one of the discussors earlier today of 1000 kw. to 12,000 kw. per sq. mi., you will see that New York City is confronted with a considerable problem in taking care of the physical side of its policy adopted during the current year, of taking on no more d-c. business on Manhattan Island.

The new Chrysler Building in upper Manhattan is 70 stories in height, nearly 1000 ft. We have in this building the problem of a network going vertically. The total transformer connections in the Chrysler Building will be of the order of 3000 kv-a.

Very briefly, the scheme of supply from the power company system to the network in the building is this: They have found it desirable to establish what I shall term a high-voltage network, that is to say, a network of 13,200-volt cables in the street which in turn are tapped into transformer vaults located in various

floors in the building. There will probably be four separate transformer vaults located strategically through the building from the basement to the roof with particular respect to the location of the load. Naturally the elevator loads, with the motor-generator sets in the top of the building, represent a point on concentrated load. To supply such a building there will probably be brought into it a minimum of four of these 13,200-volt cables. There are no switches provided in the 13,200-volt system within the building, the high-tension switching being conducted at the power company substations. Full dependence is placed upon the network protectors, as emphasized by Mr. Blake, in clearing the building in all its network from any faults which occur on the high-tension system beginning with the transformer.

The power company will own the high-tension cables and the transformers. The building will supply the transformer vault space and all the low-tension network. I shall leave to your imagination, the comparison of the tremendous decrease in building low-tension copper which results in these enormous structures when the supply is through the low-tension a-c. network as compared to the tremendous lot of copper which would be required to bring all of this capacity from the basement of the building to the roof.

W. H. Johnson: In the last two months we have placed a low-tension a-c. network system in service in Evanston, Illinois, a very small one in comparison to the one outlined by Mr. Sinclair, but the load is rapidly increasing and the primary reason for installing this system was the necessity for a high standard of service, and the system we are discussing today supplies that need and justifies its application.

I was particularly interested in the actual results of cable tests run by the Duquesne Light Company. I believe we should have more discussion on a very common problem, that is, voltage fluctuations on account of the combined light and power on one set of mains, the principal causes of voltage variation being due to the starting current characteristics of motors.

I should like to know of Mr. Sinclair's experience with motor-starting devices which restrict the motor starting currents to definite increments in order to prevent excessive fluctuations in voltage. Some resistance type starters will normally keep the voltage within proper limits so as not to be objectionable, but we understand that after working them for a short time a customer can jam the starter and the result is, increased voltage fluctuations which are naturally objectionable to the service rendered.

M. T. Crawford: (by letter) In this paper is described a number of excellent and original features which are of profound interest to operators of networks systems, and I should like to ask a few questions.

What were the underlying reasons for the decision to divide the Pittsburgh networks systems into separate sections, other than the fact that different primary voltages were to be used in two portions of the area?

We have been trying to decide if the Seattle networks system should be split or extended as a unit. It covers an area about the same as in Pittsburgh, one-half square mile, but is oblong, and the load is about 15,000 kw. In nearly nine years operation it has cleared itself of all troubles and no experience indicates the need of splitting on the secondary side. In one case of trouble where all networks switches were located out in a radius of several blocks, the service was maintained with a minimum of 90 volts near the trouble for an hour while service men replaced switches. The secondary mains fed in heavily from outlying sections with no damage except a few bulged splices.

The separation of transformer and network switch compartments is a distinct advance for high-voltage heavy-duty service. It would be of great interset to know the factors influencing the selection of varnished cambric cable for the vulnerable secondary transformer leads, in preference to rubber-covered braided cable, or perhaps lead-covered cable with insulating joints to permit ground isolation of the sheath. Will the cable selected stand up in the flood area?

At points where the load density required up to seven 300-kw. transformers at one location, what were the economies as compared with several larger sized transforming units.

C. T. Sinclair: As far as Mr. Blake's remark relative to the trip-free mechanism is concerned, he is correct in his assumption. Our statement should be interpreted to apply only to the motor-driven mechanism because only in the case of the motor-driven mechanism is that problem as we have described it here.

Mr. Richter brings out a number of points, one of which I wish to mention, and that is the question of feeder regulator. He is quite right when he says that the feeder regulator cannot be omitted in all cases. I would not even go so far as to say it can be omitted in the majority of cases. Our particular position is that there is a number of systems where it can be omitted, and where it can be omitted it is just one less piece of equipment, as far as service maintenance cost is concerned. We eliminate it where we can.

The next point I think was Mr. Hamill's. He mentioned the fact that they had three feeder faults thus far, and they had all cleared. Normally, we do not boast about feeder faults, but we have had eleven or twelve of them and they have all cleared. We hope we do not have to clear any more. We recently had a transformer failure which broke the casting in four parts without any network trouble. I was very much interested in the statement that Mr. Hamill's company checks the breaker operation every day. We do not go quite so far. We rotate our feeders, one a night in each of the network sections. I rather think this proposal is somewhat safer, although I believe rotating them one a night is adequate. I like his idea of using the red and green lights so that the inspector does not have to get out of his car to see whether the switch is open or closed. We have considered that but there are some local conditions which make it undesirable.

Mr. Eales mentioned the Chrysler Building in New York. We have a similar problem in Pittsburgh. The structure to which I refer is 600 ft. high which we think is going to prove economical on the basis of vertical distribution.

Mr. Johnson brings up an important subject I am sorry we did not have time to discuss at length, and that is the question of voltage fluctuation. Considering the details of the several types of starters that are available, we have used the carbon-pile starter with considerable success. We have had them in operation for a number of years, and with normal operation and maintenance they have been very satisfactory. There is a number of types of step-by-step resistance starters available which are very sturdy and which thus far have given no trouble, although quite frequently they are a little more costly, dependent on motor size. I might say this, that everyone in starting in a network is usually quite worried about this problem not only of lamp voltage but of voltage fluctuation, and I think it is customary to come to the conclusion that the problem of voltage fluctuation is not serious. As the network becomes larger your secondary bus becomes stiffer, and the problem of lamp flicker is not a serious one. There are individual cases where we find a motor or a starter that gives trouble, but usually there is some solution. Thus far we have not found any problem of that sort that we haven't been able to take care of.

Mr. M. T. Crawford in his letter has raised the question as to the underlying reasons for the decision to subdivide the Pittsburgh Network System into separate sections. The fact that different primary voltages were used in the two portions was not in itself a determining factor for this subdivision. Both the 4-kv. and 11-kv. systems are designed to operate in parallel and have been so operated. The principle purpose in the sectionalizing scheme is to permit any section to be shut down completely without affecting the others.

The design of the system is such as to permit the combination of these sections or the further subdivision if operating experience indicates that either is desirable.

In answer to Mr. Crawford's second question as to the factors influencing the selection of varnished-cambric cable for the vulnerable secondary transformer leads, I may say that both rubber-covered braided cable and lead-covered cable with insulating joints were considered. There is no serious objection to the use of rubber-covered braided cable other than the fact that it has a somewhat lower current-carrying capacity than the varnished cambric. The lead-covered cable with insulating joints should be satisfactory but is somewhat more costly and requires additional lead work in the vault. The flameproof cable mounted on insulators is a cheap and satisfactory method of accomplishing the purpose. This cable has been operated under water for long periods of time.

The third point raised by Mr. Crawford relates to the use of the seven 500-kv-a. transformers at one location. Undoubtedly several larger size transformers would have been satisfactory. There is a limit, however, to the network switch sizes available. Considering this, with the fact that 300- and 500-kv-a. transformers and equipment is standard for our system, led us to choose the 500-kv-a. size. For example, the seven 500-kv-a. transformers in this particular installation could possibly have been replaced by three 1200- or four 1000-kv-a. units. However, the standard network switch available today is not large enough for this size unit. It was felt undesirable to attempt to operate two of these switches in parallel which might have been the solution.

Referring to Mr. Richter's discussion I note that he makes the statement that external reactors used to increase the bank impedance to a total of 10 per cent saturate under short-circuit current, and therefore the normal impedance furnishes more short-circuit current to a secondary fault and thus the fault will clear quicker. It should not be interpreted from this statement that a 5 per cent impedance transformer furnishes a short-circuit current to a given fault twice that furnished with a 10 per cent transformer with inherent impedance. As a matter of fact short-circuit calculations indicate that the total amount of current furnished an average vault using 5 per cent transformers is not greatly in excess of the short-circuit current furnished from a system utilizing 10 per cent transformers with inherent impedance. This is due to the fact that the short-circuit current furnished from the 10 per cent system reaches out further into the network as far as the surrounding transformers are concerned.

To illustrate this I have taken a point on our system at random which shows that with 5 per cent transformers the total current to a given point approximately midway between two transformer banks is 8000 amperes in one direction and 11,000 in the other, or a total of 19,000 amperes. The same point calculated with 10 per cent transformers shows 7200 amperes in one direction and 9800 amperes in the other, or 17,000 amperes total.

An Economic Study of an Electrical Distributing Station

BY W. G. KELLEY[1]

Fellow, A. I. E. E.

Synopsis.—*This paper outlines some of the physical reasons and economic advantages influencing the establishment of Washington Park Distributing Station of the Commonwealth Edison Company of Chicago.*

This station is located at the electrical center of the load which it supplies. It receives energy at 66 kv. from an outlying generating station, State Line Station. The voltage is reduced at the distributing station and fed to a number of substations at 12 kv.

The past practise of this company has been to feed the substations at 12 kv. directly from generating stations. However, a study indicated several reasons for discarding the practise in this case.

The main physical reasons were the congested condition in the underground cable system surrounding Calumet Generating Station and the distance from Calumet Station to its dependent substations.

The economic advantages consisted primarily of the decrease in transmission line costs due to the location of the distributing station at the center of the zone load and the savings resulting from the use of 66-kv. instead of 12-kv. for the primary transmission system.

THE subject matter contained in this paper is confined to a study of the transmission costs incident to the establishment of the Washington Park Distributing Station of the Commonwealth Edison Company of Chicago.

A distributing station differs from a generating station in that it receives electrical energy over transmission lines instead of producing the energy by means of generators. The energy is usually transmitted to the station at a higher voltage and distributed from the station at a lesser voltage to a number of adjacent substations.

The three-phase electrical system supplying energy to the distributing station may be termed the primary transmission system and consists in this case of three single-conductor 750,000-cm., 66-kv. cables. The three-phase system conveying energy from the distributing station to the substations may be termed the secondary transmission system, and the feeders are in this case three-conductor, 500,000-cm., 12-kv. cables.

A map of the City of Chicago, showing the various generating stations, Washington Park Distributing Station, and the substations receiving energy from the distributing and generating stations is given in Fig. 1. The various zones or districts fed by the generating and distributing stations are also outlined on the map. As the generating stations must be located on property accessible to water for condensing purposes, they can seldom be located at the electrical center of load for their respective zones.

Table I and Fig. 2 show the load in kilowatts for the various station zones from the years 1920 to 1928, inclusive.

In the case of Calumet and Fisk-Quarry Stations, the zone loads now exceed the generating capacity and part of the energy is supplied to these two zones from State Line Generating Station by means of 66-kv. underground transmission lines.

The distribution of energy in the Calumet Station zone has introduced certain physical and economic difficulties; first, due to the high cable temperatures in

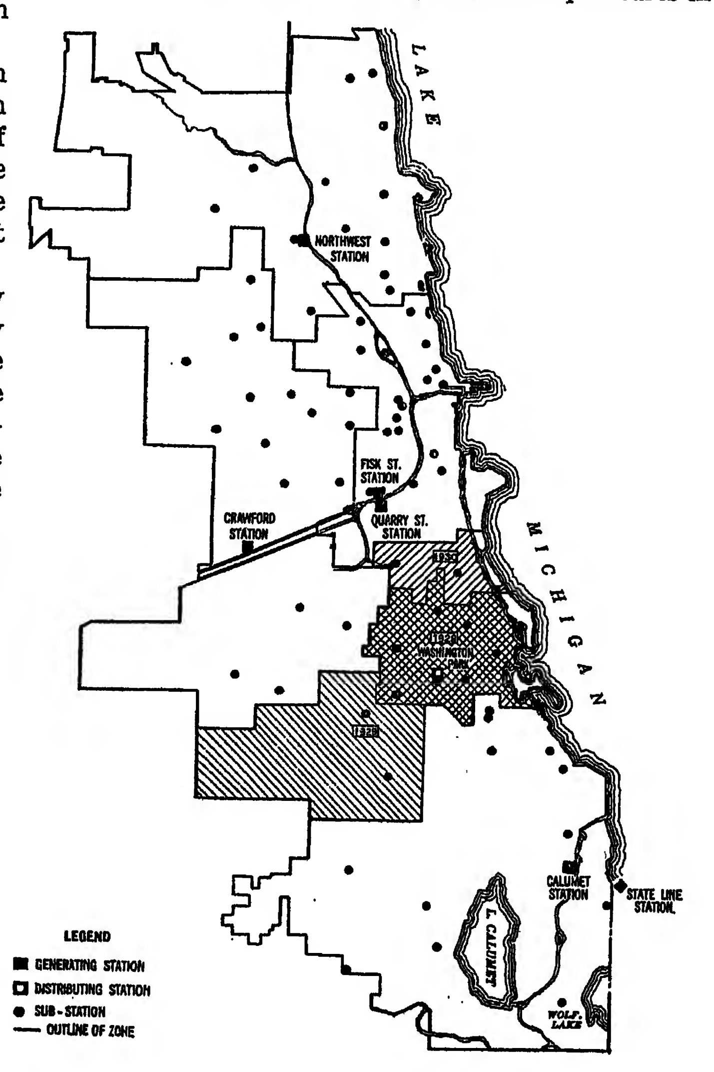

FIG. 1—MAP OF CHICAGO SHOWING THE LOCATION OF STATIONS AND SUBSTATIONS

the underground conduit system resulting from the large number of heavily loaded cables radiating to the west and north of the station; and second, due to the

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Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

TABLE I
GROWTH OF 60-CYCLE ZONE LOAD AT TIME OF SYSTEM MAXIMUM

	1920 Kw.	1921 Kw.	1922 Kw.	1923 Kw.	1924 Kw.	1925 Kw.	1926 Kw.	1927 Kw.	1928 Kw.
Northwest	50,000	65,000	81,430	91,000	84,780	101,850	118,210	128,922	143,260
Fisk-Quarry	140,000	122,000	155,200	91,980	112,985	136,276	140,220	190,840	177,723
Crawford				53,920	80,350	103,019	158,020	177,932	218,777
Washington Park									55,388
Calumet		26,000	38,770	91,290	101,187	141,885	159,000	172,952	123,880
Total	190,000	213,000	275,400	328,190	379,302	483,030	575,450	670,646	719,028

length of the 12-kv. secondary transmission lines from Calumet Station to the various substations in the zone.

The number of 12-kv. underground cables at Calumet Station is designated by the figures shown on the conduit line in Fig. 3.

Due to the fact that a considerable portion of the zone load is brought into the district at 66 kv. and not generated at Calumet Station, it was proposed that a new station be established at the electrical load center of the northern half of the Calumet zone for the purpose of receiving energy from State Line Station at 66 kv. and distributing it to the various substations at 12 kv.

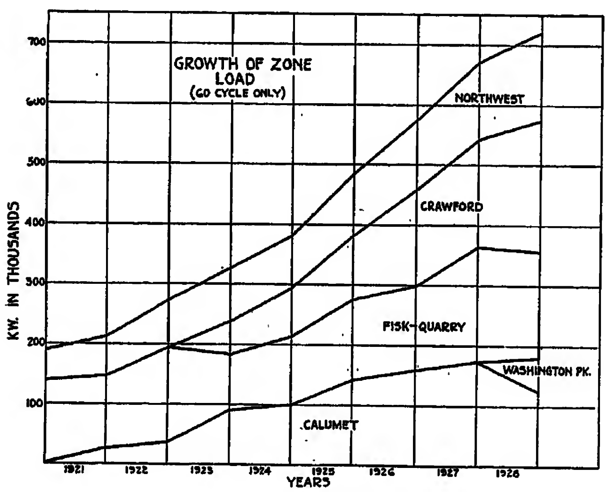

FIG. 2—GROWTH OF ZONE LOAD FOR THE YEARS 1920 TO 1928, INCLUSIVE

A preliminary study of the secondary transmission cables on the 12-kv. system expressed in circular-mil-feet per kilowatt, showed that a 10 per cent reduction in this ratio could be effected for the entire Chicago area by the establishment of Washington Park Distributing Station.

Eight substations were tentatively selected to form a zone load for the first year for Washington Park Distributing Station and for the year 1928, the load in this zone was 55,388 kw.

Table III shows the load on the eight substations selected for the years 1923 to 1928, inclusive, segregated under the three headings, four-kv., railway, and industrial load.

The average distance from these substations to Calumet Generating Station, weighted for load, was found to be 41,600 ft., while the average distance to Washington Park Distributing Station, weighted for load, was found to be only 8690 ft. This represented a marked decrease in the amount of cable necessary.

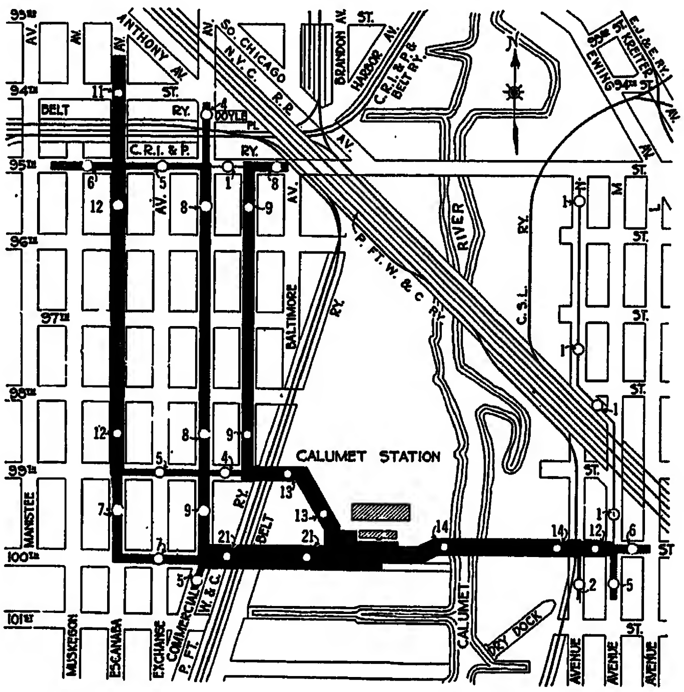

FIG. 3—DIAGRAM OF UNDERGROUND TRANSMISSION CABLES AT CALUMET STATION

The numerals denote the number of three-phase 12-kv. cables in each conduit line

TABLE II
TRANSMISSION COPPER IN 12-KV. DIRECT TRANSMISSION LINES

	Length circuit feet	Copper Volume 1,000,000 cir. mil. ft. (one phase)	Peak load	1,000,000 cir. mil. ft. per kilowatt
1923	1,961,882	728,885	328,100	2.22
1924	2,202,563	980,044	379,302	2.58
1925	2,376,517	1,079,283	483,030	2.23
1926	2,887,780	1,352,029	575,450	2.35
1927	3,183,648	1,505,647	670,646	2.24
1928	3,118,895	1,483,448	719,028	2.06

TABLE III
GROWTH OF PROPOSED WASHINGTON PARK ZONE LOAD

	1923	1924	1925	1926	1927	1928
Hyde Pk.	11,600	10,400	9,880	8,900	7,430	8,100
Prairie	5,180	4,920	5,890	5,030	4,900	5,740
62nd St.	9,100	7,820	8,825	9,270	9,400	10,200
Harper		3,660	4,450	4,300	5,300	5,210
56th St.	10,720	9,320	9,600	9,650	7,560	7,350
Lowe	760	3,100	4,530	3,950	6,360	7,400
Total 4-kv.	37,360	39,220	43,175	41,700	40,950	44,000
62nd Railway	5,760	5,520	4,140	4,130	4,070	4,058
E. 63rd Railway	.		1,970	2,670	4,000	3,370
Total Railway	5,760	5,520	6,110	6,800	8,070	7,428
Hyde Pk. Indus.			22	655	416	104
62nd Indus.			149	663	445	1,573
56th Indus.			307	436	1,148	1,460
Wash. Pk. Indus.				457	725	323
Total Indus.			478	2,211	2,734	3,460
Grand Total	43,120	44,740	49,763	50,711	51,754	54,888

and formed one of the main economic factors leading to the construction of Washington Park Distributing Station.

The following cost data were used in making the study:

12-kv. three-conductor cable......$1.95 per ft.
66-kv. single-conductor cable.. 2.64 to 3.07 per ft.
Conduit per duct............. 1.00 per ft.

Due to the fact that the energy for this zone is brought to it at 66 kv., it would have been necessary to install switching equipment, transformers, and the necessary buildings either at Calumet or Washington Park Stations, and the cost of these was assumed to be the same whether installed at one point or the other.

The cost per kilowatt of the 66-kv. primary transmission lines, with the necessary conduit from Calumet Station to Washington Park Distributing Station, was $11.40, and the total cost allocated to the Washington Park Distributing Station plan, based on the load of 55,388 kw., was therefore $630,000. The cost of 12-kv. secondary transmission lines and conduit from Washington Park Distributing Station to the eight substations, was $220,000, making a total cost for this plan, of $850,000.

The cost of 12-kv. secondary transmission lines and conduit from Calumet Station to the various substations, assuming Washington Park is not to be built, was found to be $994,000, making a difference of $144,000 capital investment in favor of the construction of Washington Park Distributing Station.

This saving is due primarily to the development of 66-kv. underground cable and the greater economy of transmission at this voltage over the use of 12-kv. cable.

It is proposed to put additional substations as shown in Fig. 1 in the Washington Park Distributing Station zone during the years 1929 and 1930, thereby increasing the zone load, and also to establish additional distributing stations in the central and northern sections of the city, when economic conditions warrant.

Experience with Carrier-Current Communication
On a High-Tension Interconnected Transmission System

BY PHILIP SPORN* and RAY H. WOLFORD*
Member, A. I. E. E. Non-member

Synopsis.—*The paper gives a historical outline of the development of carrier-current communication on power systems. It discusses the principles of the various systems of carrier current developed to date and outlines the fundamentals of a carrier communication system over a transmission network.*

A description of the installations on a 132-kv. network having an extent of 2500 linear miles is given and the general experience with carrier, which is the sole means of communication operated and provided by the power companies on that system, is outlined.

A carrier-current communication system is analyzed into its component parts and the experience with these various parts given. Extensive experience with various forms of couplings, various forms and makes of coupling capacitors is described. Experience with the protective system, the lead-in system, and the tuning used in connection with the coupling is given in detail.

Detailed experience is given with the transmitting system and the receiving system of various makes of carrier employed. An outline of the experience with the various makes of power supply is given.

A discussion of the operation of carrier on a large system such as the one described and the necessity for zoning and interzoning is given and experience in establishing and maintaining these zones is outlined. Definite data are cited as to cost, maintenance, reliability, traffic, and safety. A description of various types of portable sets developed and their use is given. Some of the lines of future development found desirable in the light of the author's experience is indicated.

Introduction

A NUMBER of papers on carrier current has been given before the Institute on various phases of carrier-current communication. Most of these papers have been presented by manufacturers' engineers. In the two cases where operating engineers have presented papers they covered operation of a carrier-current installation on either a single or on two lines, the maximum number of terminals considered being three. No paper to date has been presented either by a manufacturing or an operating group that made an attempt to give operating experience with carrier current on a transmission system or to describe a complete system of carrier-current communication.

It is quite patent that two or three sets do not make up a system and that the practicability of carrier or of any system of carrier-current communication cannot be determined from the operating results obtained with two or three sets. Besides, the isolated line utilized for transmitting a block of power from a generating point to a point of use is decidedly the minority case today, and is more likely to be so in the future. We are rapidly approaching the point where the country will be covered by a network of interconnected transmission lines. In the Chicago territory, for example, there is a solidly connected 132-kv. system operating in parallel twenty-four hours a day that runs from Twin Falls, Wisconsin, south to Kingsport, Tennessee, and to Roxboro, North Carolina, and east as far as Wheeling, West Virginia, a total lineal mileage of approximately 2500 miles and circuit mileage of approximately 3450 miles. There seems to be no reason to doubt that interconnection and the development of systems of the same type will go much further in the future.

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Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

The American Gas and Electric Company's subsidiaries have been associated with carrier current and carrier-current operation from its very inception and have been operating a larger single transmission high-voltage network than operated by any other group. The experience obtained on this network primarily and on other portions of the system in the operation and application of carrier may, therefore, be expected to be of interest to other members of the Institute.

History

The principle of multiplex telephony with which carrier current is so intimately tied up has been known for at least 38 years, the first patent disclosures having been made on it by Leblanc in 1891. The use of a pair of wires for guiding a high-frequency wave signal is due to Squier, who did his first development work on it in 1910. This was disclosed in an historic paper before the Institute in June 1911. The idea of using high-frequency current on a high-tension transmission line was previously proposed by Neu in 1905. This, however, was not carried very far for many years. Equally slow was the development of the idea proposed by Squier, the prevailing opinion of the best communication engineers at that time being that the scheme proposed by him had only limited rather than general application.

The real beginning of development of carrier communication on power lines can be stated to have begun with 1920. In July 1920 an experimental installation of carrier telephony, the result of the conception and work of Tidd, Sindeband, and Milnor, was made on the system of the American Gas and Electric Company between Atlantic City and Ocean City, New Jersey, over an 11,000-volt transmission line. An account of these tests appears in the July 17, 1920 issue of the *Electrical World*, from which the following is quoted:

"At last successful telephone communication has been conducted over live high-tension lines by the American

Gas and Electric Company, which has been convinced thereby that the method employed will solve one of its most important problems, namely, a reliable and less expensive mode of communication between its load dispatchers and interconnected stations.

"The tests which proved the practicability of the method were conducted . . . between the company's Atlantic City and Ocean City stations over a live 11,000-volt, 60-cycle transmission line, 12 miles (19.2 km.) long. Between the transmitting and receiving sets were the windings of the power transformers at both ends of the line and an underground cable, making the equivalent length of transmission about 21 miles (33.6 km.). The carrier current for the communications was at a frequency in excess of 5000 cycles. The transmitting and receiving sets were connected with the 2300-volt buses at each station."

In this test coupling to the power line was accomplished in three ways:

(a) Through a chain consisting of a current transformer secondary and primary, plus a power transformer stepping up from the voltage of the current transformer primary to the voltage of the transmission line.

(b) Through a double transformation consisting of a potential transformer secondary and primary in series with a power transformer stepping up to the voltage of the transmission line.

(c) Through the secondaries of the bushing transformers in the bushing of an oil switch operating at the voltage of the transmission line.

In the same year coupling wires were first used to couple the carrier to a high-tension line on the 135-km., 110-kv. line between Golpa and Runnelsberg in Germany. In the same year again, condenser coupling on a 22,000-volt line was first used in connection with carrier on a transmission line in Japan.

The impetus given by all of these installations resulted in the work being taken up by American manufacturers, and in December, 1921, the first American commercial carrier set was demonstrated; the first commercial installation was made about a year later, in November 1922.

In the meantime the development work was continued on the A. G. & E. system, and in July 1921, tests were conducted on the Windsor-Canton 132-kv. line with the same type of transmission as had previously proved successful over the Atlantic City Electric Company's line. The carrier in these tests was placed on the high-tension transmission line through the secondary of an 11,000-volt current transformer; from the 11,000-volt end connection was made to the high-tension 132,000-volt line through standard power transformers. Voice communication was not quite successful in these tests, although code communication was established very successfully. The higher impedance of the high-voltage transformers undoubtedly was the major cause for the failure to go through successfully.

Shortly after that, owing to the fact that the carrier-current problem was undertaken so vigorously by the regular electrical manufacturers, development work on the A. G. & E. System was entirely suspended and none has been carried out since except for full cooperation with all manufacturers who have evinced an interest in advancing this particular art. Today there are on the system of the A. G. & E. Co.'s subsidiaries, either in operation or in process of installation, a total of 50 carrier-current sets exclusive of portable equipments.

Principles of Operation of Various Systems Developed

The carrier telephone equipments developed by the various manufacturers in this country may be classified as follows:

(a) Simplex, single-frequency, ground return.
(b) Simplex, single-frequency, inter-phase.
(c) Duplex, two-frequency, inter-phase.
(d) Duplex, single-frequency, inter-phase.
(e) Duplex, single-frequency, single-sideband, suppressed carrier.

Some of these are of course no longer being produced today.

A brief description of the above types of equipments and the communication facilities provided by each type will be given.

The first power line carrier telephone equipments developed in the United States were of the simplex ground return type. The same frequency was used for both transmission and reception, particularly where a system comprised more than two stations.

To prevent the transmitter from reacting upon the receiver, a manual switching control was used to render the transmitter inoperative during reception, and to render the receiver inoperative during transmission. Coupling to the transmission line was usually secured by stringing an antenna approximately 2000 ft. long parallel to the power conductors, the same antenna generally being used for both transmission and reception.

It was soon observed that the noise level secured by the ground return system could be greatly reduced by employing a full metallic carrier-current circuit, resulting in the development of sets using two antenna conductors coupled to different phases of the transmission line.

Although experience showed that the simplex manually controlled type of sets was capable of giving a high quality of communication, still these sets required a certain amount of skill in using them on account of the necessity of manual control of transmission and reception. The demand arose for equipment with which communication could be carried on without the use of manual control, leaving the control to automatic devices, thereby resulting in the development of duplex type equipment, that is equipment providing for simultaneous transmission in both directions.

In order to secure the duplex feature, the various

manufacturers resorted to different means. The Westinghouse Electric & Manufacturing Company developed duplex equipments, using a system employing two carrier frequencies, one frequency for transmission and the other for reception.

In their system the carrier frequency is transmitted continuously during the operation of the equipment, that is, during receiving periods the carrier frequency is transmitted but not modulated. Coupling to the transmission line is usually made by two antennas for

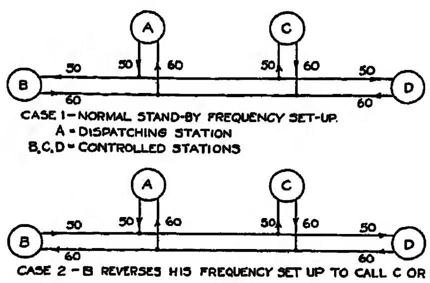


Fig. 1—Schematic Diagram Illustrating Communication Provided by the Westinghouse Electric and Mfg. Co. Two-Frequency Duplex System

transmission coupled inter-phase to the transmission line.

Fig. 1 shows schematically a system of four stations arranged to communicate with each other. Station *A* is the main control or dispatching station, and stations *B*, *C*, and *D* are controlled stations. The system operates as follows: Under normal standby conditions, station *A* is adjusted to transmit at a frequency of, say, 50 kilocycles and to receive at 60 kilocycles. Stations *B*, *C*, and *D*, are adjusted to

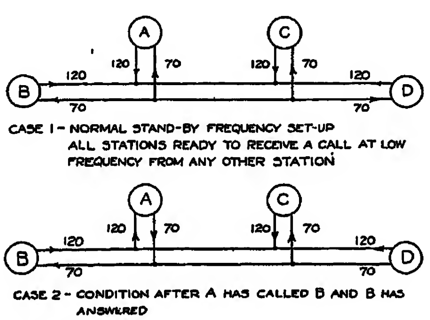


Fig. 2—Schematic Diagram Illustrating Communication Provided by the Western Electric Co. Two-Frequency Duplex System

transmit at 60 kilocycles and receive at 50 kilocycles. Under the normal condition *A* may call and talk to either *B*, *C*, or *D*, but *A* having established communication with *B*, then *C* and *D* are not able to establish communication with each other nor with *A* or *B*. Either *B*, *C*, or *D* may also call and talk to *A*. *B* desiring to call and talk to *C* or *D* may do so by reversing his frequency set-up, but having done so cannot talk to *A*. This system therefore provides a means for any two stations on a channel calling and talking to each other, at which time all other stations on the system cannot be in communication with the two stations which are talking, nor with each other.

The Western Electric Company also developed duplex equipments using a two-frequency system similar to the one just described. This system likewise employs continuous transmitted carrier frequency.

Fig. 2 shows schematically a system of four stations arranged to communicate with each other. In this system the receivers of all stations are normally set to receive a call at the lower freqeuncy. Calling stations transmit at the lower frequency and receive at the higher frequency from the called station. With this arrangement, all the stations on a channel are equally able to call and talk to any other station on the channel. However, if any two stations, for example *A* and *B*, are talking to each other it is not possible for any other two stations to carry on a separate communication or to carry on a communication with either *A* or *B*. While *A* and *B* are talking, stations *C* and *D* are able to hear one side of the *A* and *B* conversation, the side available depending upon whether *A* or *B* originated the call.

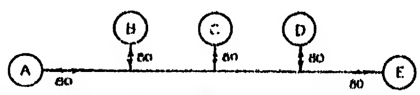


Fig. 3—Schematic Diagram Illustrating Communication Provided by the General Electric Co. Single-Frequency Duplex System

Any station is in position to call and talk to any other station; full party line service is provided for either giving general orders or for conference

The original two-frequency, duplex equipments produced by the Western Electric Company were designed for use with two antenna wires for coupling inter-phase to the transmission line. However, when the use of high-voltage coupling capacitors came into use, the equipments were modified for capacitor coupling.

The duplex type equipments developed by the General Electric Company employ one frequency used for both transmission and reception in contrast to the two different frequencies used by the other manufacturers mentioned. The single-frequency duplex equipment functions similarly to the simplex single frequency sets which were first developed by the General Electric Company, except that the control of the transmitter and receiver is made automatic instead of manual by the use of vacuum tube relays. This results in a system in which the carrier frequency at a station is only transmitted at the time of speaking, no carrier being transmitted during receiving periods. The system works as follows. Fig. 3 shows a group of five stations on a channel, the transmitters and receivers of all stations being tuned to the same frequency. Any station—*A* for example—may call and talk to any other station, such as *B*. While *A* and *B* are talking all other stations on the channel—that is *C*, *D*, and

E—can hear the entire conversation of both A and B and may join in and participate in the conversation. That is, this system provides a means so that simultaneously all stations on a carrier channel may be in communication with each other, provided, of course, that the conversation is orderly and two parties do not attempt to speak at once.

The two-frequency duplex type of equipments, as mentioned above, are both capable of giving a true duplex communication channel. That is, when two parties on a channel are talking, no interference to the operation of the equipment will result if both parties should speak at the same time. With the single-frequency duplex equipment as produced by the General Electric Company, it is possible for communication to be disturbed when two parties speak at the same time. However, experience with the use of these equipments has shown that for all practical purposes, duplex operation is secured for the reason that during orderly conversation between two parties, only one party speaks at a time.

The duplex two-frequency inter-phase equipments of the Western Electric Company now have been superseded by a duplex single-frequency, single-sideband suppressed-carrier system. None of this latter equipment is in operation at the present time on the A. G. & E. Co. system. In this system, after the carrier frequency has been modulated by the voice signal, one sideband and the carrier frequency are eliminated and only the other sideband transmitted. At the receiving end a locally generated carrier frequency is combined with the received single sideband and the resulting modulated carrier frequency demodulated to produce the audible frequency. This system provides a duplex carrier channel similar to the single-frequency duplex equipment produced by the General Electric Company and enables all the stations on a channel to be in simultaneous communication with each other, providing, of course, that two parties do not speak at the same instant.

Fundamentals of a Carrier Communication System over a Network

It would seem well to outline the fundamentals of a carrier-current communication system for communication over power lines in order to be able to interpret properly the experience that will be described here. Attention should be called to the fact that the experience described covers experience obtained on a system or a network and not on isolated lines. The tendency, as previously pointed out, is toward the development of fewer and larger systems, in other words toward high-tension networks.

The author's experience has been that most literature emanating from manufacturers or manufacturers' representatives has not been sufficiently free from the commercial point of view. Scientific accuracy seems to have been sacrificed in too many cases to talking points. As an example, in one paper presented before the Institute, the author placed the fundamentals at three. In another technical paper, however, in an article from a different manufacturing group, the total number of fundamentals is listed alphabetically, and the alphabet is almost completely exhausted before the entire series is enumerated. In each case of necessity each manufacturer's equipment completely met the fundamental requirements set up by him. This, of course, has made the problem of deciding for or against and proper application of carrier on the part of the power system engineer all the more difficult, and undoubtedly it has not helped the advancement of the carrier-current art.

What really are the fundamentals? Based on our experience with an interconnected system, by which is meant a system consisting of an extended high-tension transmission network sufficiently extended, as to have more than one dispatching point, the following fundamental requirements are of primary importance:

1. Ability to carry on more than two conversations on any channel; in fact, ability to carry on as many conversations on a channel as there are stations in a channel, simultaneously. This automatically means the ability of any one station on a channel to cut in on a conversation if it has anything of an emergency nature to report or if it has any information to contribute to the business that is being discussed.

It is to be noted that this is a definite reversal of what is considered a prerequisite in ordinary telephone conversations where it is considered as an absolute essential that nobody, unless particular arrangements for it have been made, be able to cut in on a two-party conversation. Those who have had experience in the operation of transmission and power systems will realize the absolute necessity for this requirement.

2. Reliability. This is so fundamental that it is almost axiomatic. Under this can be included therefore such items as simplicity, safety, ease of maintenance, and all other items that contribute to reliability.

Here again, it may be of interest to point out that in the early days carrier was looked upon by many people as a very good standby service for other means of communication, which would be used normally. The experience which we shall cite later will show that it has been possible to bring about a reversal of the situation in that carrier can be made to continue to function when other forms of communication fail.

3. Ability to furnish a maximum number of channels on any one system. This of course assumes that the system is big enough to require more than one channel; in fact, it assumes that the system is so big, and this has been brought out previously, that more than one dispatching point is utilized, and it therefore becomes imperative, in order to be able to carry on the business of the system effectively and expeditiously, to confine a particular channel to a definitely limited geographical area. As a direct corollary to that is the statement

that the system must use only one frequency for transmitting and receiving, and the selectivity between various channels must be of a very high order. It is obvious of course that the use of two frequencies per channel automatically cuts in half the number of possible channels available in any particular band of frequencies.

comprises 2500 linear miles of 132-kv. transmission line and 3450 miles of circuit, of which the portion in solid represents 1340 linear miles of transmission and 2050 circuit miles operated by American Gas and Electric Company subsidiaries, and the dotted portion indicates the foreign lines. No attempt will be made to give any experience with sets on foreign lines. They are shown

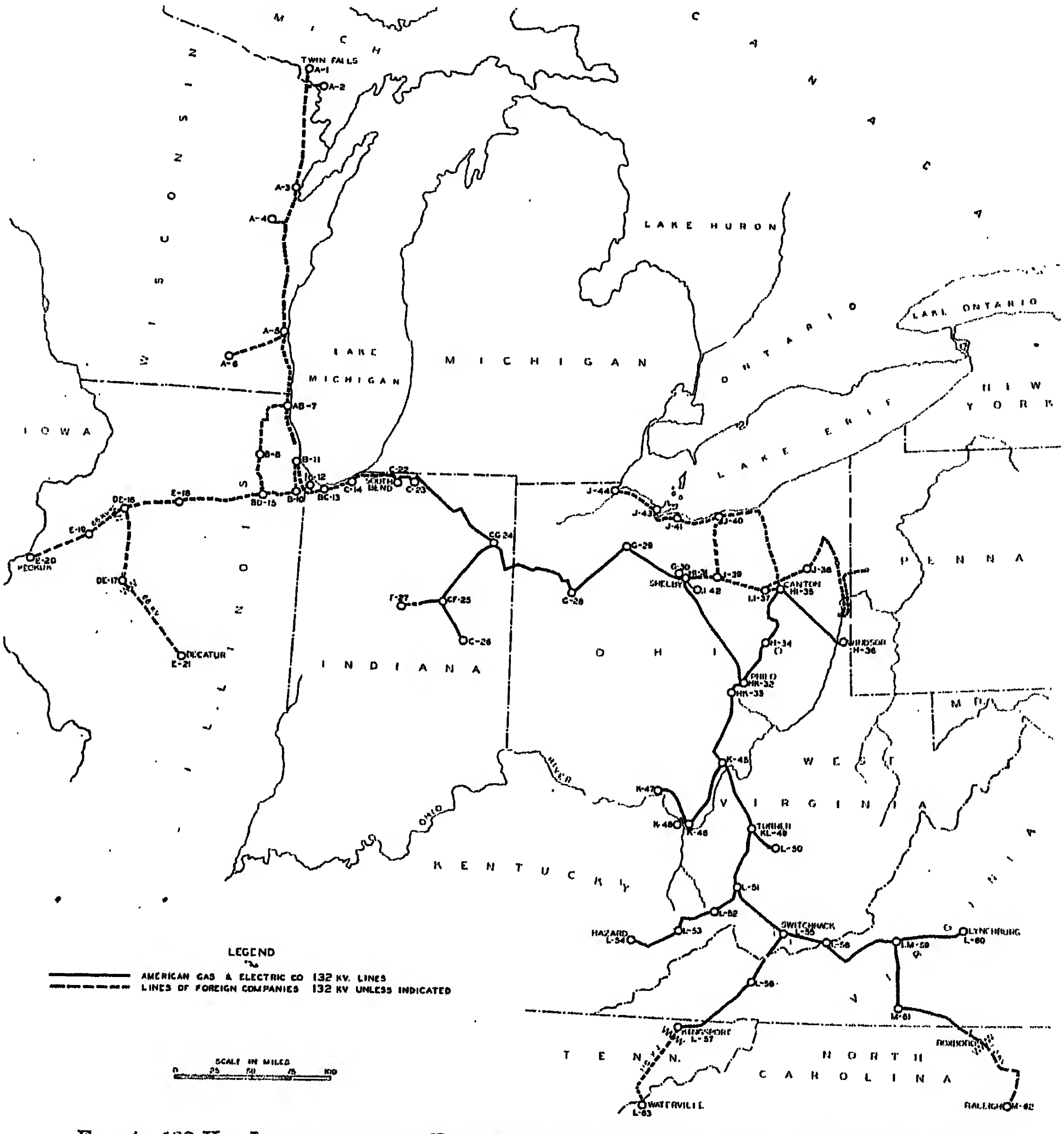


Fig. 4—132-Kv. Interconnected Transmission System and Location of Carrier Sets

The above we have found, as a matter of experience covering a period of ten years, to be the fundamentals. Our experience and our opinions with regard to the performance obtained will be understood more clearly when considered in the light of these fundamentals.

Description of Installations on American Gas and Electric System and General Experience

Fig. 4 shows the 132-kv. system in question. It

here for the reason that they have a bearing on the problem since they are all located, as already pointed out, on a single 132-kv. transmission network that extends from Twin Falls, Wisconsin, south to Kingsport, Tennessee, and Roxboro, North Carolina, and east as far as Windsor, West Virginia. The system of the American Gas and Electric Company is operated from five central dispatching points as follows: South Bend, Indiana, Shelby, Ohio, Canton, Ohio, Turner

(Charleston), West Virginia, and Switchback, West Virginia. District dispatchers are located at practically every 132-kv. station of importance.

The dots on the map indicate the location of sets; that is, each dot represents a single set. Table I gives the details with regard to these sets. This table will be referred to again later.

All these sets are single-frequency, duplex operation, selective ringing sets of General Electric manufacture. They operate in this network over 14 channels and of these 14 channels 9 are utilized by the subsidiaries of the American Gas and Electric Company.

The general experience with this system of carrier on the 132-kv. system has been highly satisfactory from the very beginning. There were troubles in the early days with the simplex sets, particularly with the simplex ground return sets in signaling, in getting through, and in the quality of speech; troubles were experienced in getting the proper signal strength in the early days when antenna coupling was employed; difficulty was experienced with the growth of the system and the number of sets in maintaining proper separation between the various channels; there was experienced some trouble with some of the types of coupling capacitors employed as will be brought out later; but on the whole carrier has for the past five years provided on this system the means of load dispatching and the means of maintaining contact on all similar and related business without any outside supplement. Again and again when all other sources of communication in a particular district failed, carrier continued to provide service of the same high type and of the same high quality as it provided under normal conditions.

In brief, the experience on the whole with carrier has been highly satisfactory. Its development on our system has demonstrated the fact that carrier on our system has reached a stage where it will, if properly applied, provide a quality of communication with a reliability that is generally obtainable at present through no other source at the same cost. Further, our experience has been that those of the equipments that were built and developed in the earlier

TABLE I

CARRIER-CURRENT COMMUNICATION STATIONS AND CHANNELS A. G. E. 132-KV. TRANSMISSION SYSTEM AND INTERCONNECTING 132-KV. SYSTEMS

Reference	Channel reference letter		Frequency in kilocycles		Location of set	Operating company
A- 1	A		50		Twin Falls, Mich.	Wisconsin Public Service Co.
A- 2	A		50		White Rapids, Mich.	Northern Electric Co.
A- 3	A		50		Green Bay, Wis.	" " "
A- 4	A		50		Appleton, Wis.	Wisconsin Public Serv. Co.
A- 5	A		50		Milwaukee, Wis.	Milwaukee Elec. Ry. & Lt. Co.
A- 6	A		50		White Water, Wis.	" " " " "
AB- 7	A	B	50	110	Waukegan, Ill.	Public Service Co. of Northern Illinois
AB- 7	B	A	110	50	Waukegan, Ill.	" " " " "
B- 8	B		110		Electric Jct., Ill.	" " " " "
BD-15	B	D	110	60	Joliet, Ill.	" " " " "
B-10	B		110		Chicago Hgts., Chicago, Ill.	" " " " "
B-11	B		110		108th St. Substa., Chicago, Ill.	Commonwealth Edison Co.
C-12	C			85	Hammond, Ind.	Northern Indiana Public Service Co.
BC-13	B	C	110	85	Aetna Sub., Ind.	" " " " "
C-14	C			85	Michigan City, Ind.	" " " " "
BD-15	D	B	60	110	Joliet, Ill.	Public Service Co. of Northern Illinois
DE-16	D	E	60	72	Kewanee, Ill.	Illinois Pr. & Lt. Co.
DE-17	D	E	60	72	Powerton, Ill.	Super Power Co. of Ill.
E-18	E		72		La Salle, Ill.	Illinois Pr. & Lt. Co.
DE-16	E	D	72	60	Kewanee, Ill.	" " " "
E-19	E		72		Galesburg, Ill.	" " " "
E-20	E		72		Keokuk, Ill.	" " " "
DE-17	E	D	72	60	Powerton, Ill.	Super Power Co of Ill.
E-21	E		72		Decatur, Ill.	Illinois Pr. & Lt. Co.
BC-13	C	B	85	110	Aetna, Ind.	Northern Indiana Public Service Co.
C-22	C		85		South Bend, Ind.	Indiana & Michigan El. Co.
C-23	C		85		Twin Branch, Ind.	" " " "
CG-24	C	G	85	125	Ft. Wayne, Ind.	" " " "
CF-25	C	F	85	115	Marion, Ind.	Indiana General Service Co.
C-26	C		85		Muncie, Ind.	" " " "
CF-25	F	C	115	85	Marion, Ind.	" " " "
F-27	F		115		Kokomo, Ind.	Indiana Electric Corp.
CG-24	G	C	125	85	Ft. Wayne, Ind.	Indiana & Michigan Elec. Co.
G-28	G		125		Lima, Ohio	The Ohio Power Co.
G-29	G		125		Fostoria, Ohio	" " " "
G-30	G		125		Shelby, Ohio	" " " "
HI-31	H	I	46	90	Shelby, Ohio	" " " "
HK-32	H	K	46	60	Philo, Ohio	" " " "
HK-33	H	K	46	60	Crooksville, Ohio	" " " "
H-34	H		46		Newcomerstown, Ohio	" " " "
HI-35	H	I	46	71	Canton, Ohio	" " " "
H-36	H		46		Windsor, W. Va.	" " " "
HI-31	I	H	90	46	Shelby, Ohio	The Ohio Power Co.
IJ-37	I	I	90	71	Massillon, Ohio	Ohio Public Service Co.
HI-35	I	H	71	46	Canton, Ohio	The Ohio Power Co.
IJ-37	J	I	71	90	Massillon, Ohio	Ohio Public Service Co.
J-38	J		71		Alliance, Ohio	" " " "

TABLE I—(*Continued*)

CARRIER-CURRENT COMMUNICATION STATIONS AND CHANNELS A. G. E. 132-KV. TRANSMISSION SYSTEM AND INTERCONNECTING 132-KV. SYSTEMS—*Continued*

Reference	Channel reference letter		Frequency in kilocycles		Location of set	Operating company
J-39	J		71		Ashland, Ohio	Ohio Public Service Co.
J-40	J		71		Lorain, Ohio	" " " "
J-41	J		71		Sandusky, Ohio	" " " "
J-42	J		71		Mansfield, Ohio	" " " "
J-43	J		71		Port Clinton, Ohio	" " " "
J-44	J		71		Toledo, Ohio	Toledo Edison Co.
HK-32	K	H	60	46	Philo, Ohio	The Ohio Power Co.
HK-33	K	H	60	46	Crooksville, Ohio	" " " "
K-45	K		60		Rutland, Ohio	" " " "
K-46	K		60		South Point, Ohio	" " " "
K-47	K		60		Portsmouth, Ohio	" " " "
K-48	K		60		Ashland, Ky.	Kentucky & W. Va. Pr. Co.
KL-49	K	L	60	79	Turner, W. Va.	Appalachian Elec. Pr. Co.
KL-49	L	K	79	60	Turner, W. Va.	" " " "
L-50	L		79		Cabin Creek, W. Va.	" " " "
L-51	L		79		Logan, W. Va.	" " " "
L-52	L		79		Sprigg, W. Va.	" " " "
L-53	L		79		Clear Creek, Ky.	Kentucky & W. Va. Pr. Co.
L-54	L		79		Hazard, Ky.	" " " " "
L-55	L		79		Switchback, W. Va.	Appalachian Elec. Pr. Co.
L-56	L		79		Saltville, W. Va.	" " " "
L-57	L		79		Kingsport, Tenn.	Kingsport Utilities, Inc.
L-58	L		79		Glenlyn, Va.	Appalachian Elec. Pr. Co.
LM-59	L	M	79	52	Roanoke, Va.	" " " "
L-60	L		79		Rousens, Va.	" " " "
LM-59	M	L	52	79	Roanoke, Va.	" " " "
M-61	M		52		Fieldale, Va.	" " " "
M-62	M		52		Raleigh, N. Car.	Carolina Pr. & Lt. Co.
L-63	L		79		Waterville, N. Car.	Tennessee Public Service Co.
L-64	L		79		Canton, N. Car.	" " " "

days and that were therefore not able to render the service that is rendered by the newly built sets can with a reasonable amount of expenditure and effort be revamped and brought up to give substantially the same service as those that are being put out today and where

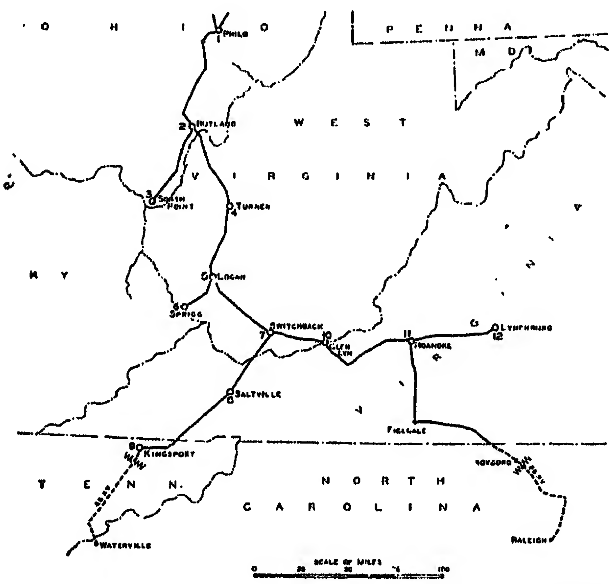


FIG. 5—POINTS ON A. G. & E. CO. 132-KV. SYSTEM WHERE WESTERN ELECTRIC CO. SETS WERE LOCATED

we have had sets of that type, they have been or are being brought up to that level.

The marked physical change in the development of these sets is shown by Figs. 6 and 7, respectively. Fig. 6 shows one of the early 50-watt simplex sets built for duplex operation on the 27-kv. system of the Indiana & Michigan Electric Company. Fig. 7 shows one of the latest CC-8B, 50-watt sets (Reference No. G-29, Table I) also installed within the last two years. The latest development of the set shown in Fig. 7, the KCA-1, has practically the same appearance and is

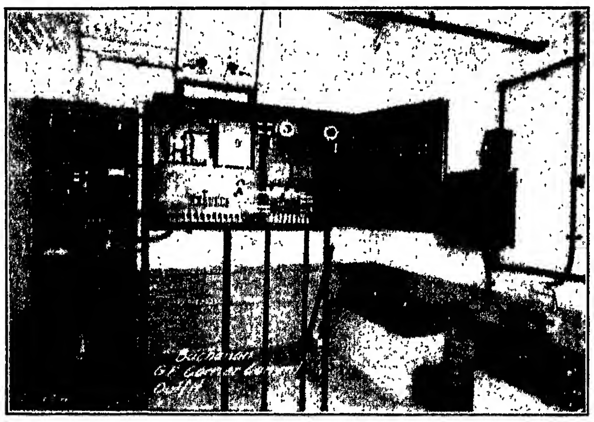


FIG. 6—EARLY TYPE OF GENERAL ELECTRIC CO. 50-WATT SINGLE-FREQUENCY DUPLEX SET

electrically practically the same, the only difference being in the physical detail of wiring.

Fig. 5 shows the southern portion of the A. G. & E. Co. system. It will be noted that the portion of the system considered starts at Philo and extends south to Kingsport and to Lynchburg. On this system there were installed at one time 12 Western Electric sets, the locations of these sets being indicated by a dot. Here

the operation of the sets was continued for a period of approximately three years, at the end of which time the sets were all removed and put in service on more isolated networks operating at a lower voltage. Fig. 8 is typical of one of these sets.

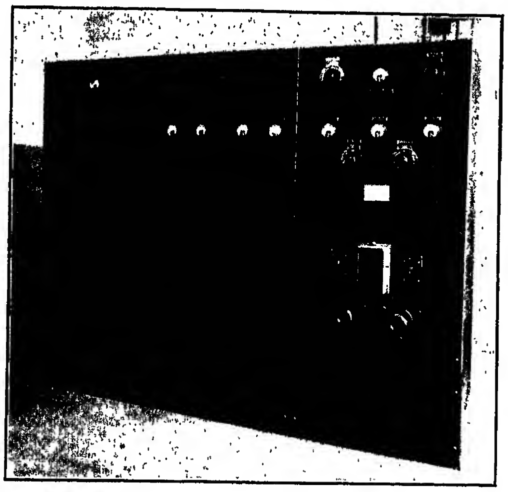


Fig. 7—General Electric Co. 50-Watt Primary Set, Type CC-8B, Ohio Power Co., Fostoria, Ohio

The main difficulty experienced with these sets was the fundamental difficulty brought about by the two-frequency system, which did not permit more than two conversations to be carried on at the same time. It

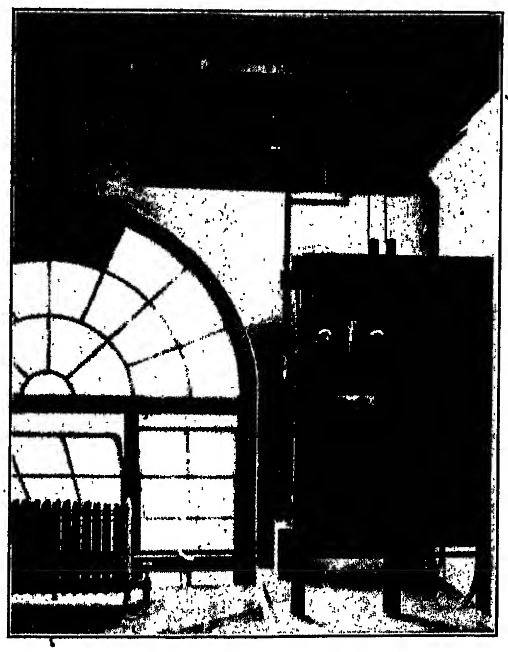


Fig. 8—Western Electric Co. 50-Watt Set

was found that such a restriction almost crippled the system and in a number of cases resulted in very bad interruptions as a result of the fact that a station in trouble could not get in touch with the central dispatcher taking care of that particular district since the dispatching point was in communication at that time with some other station on the system. Attempts were made to revamp these sets for single-frequency operation but economic considerations determined their removal to points where they could be used without any change and without the great expenditures which would have been otherwise called for. There were other difficulties experienced with the sets but by

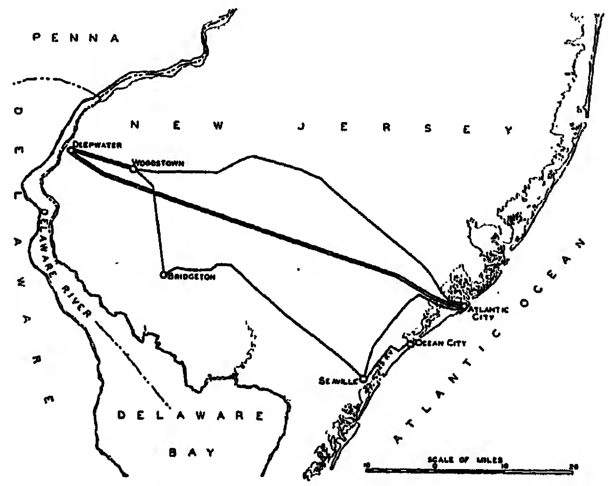


Fig. 9—66-Kv. Transmission System of the Atlantic City Electric Co. Showing Location of Sets

comparison with the main difficulty, they were of a minor nature. For example, the two-frequency system operation was also found to result in great difference in signal level received at various stations due to the unequal attenuations of the two frequencies along the system. These resulted in low voice levels and also considerably affected the reliability of the signal system employed.

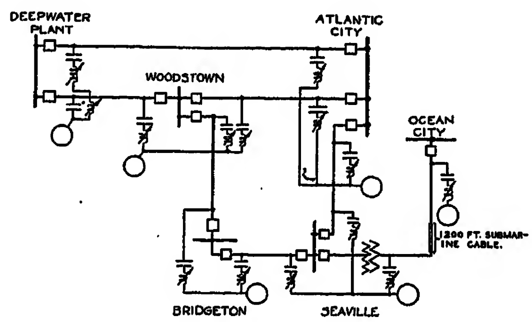


Fig. 10—Schematic Diagram Showing Coupling and By-Passing on Atlantic City Electric Co. System

Fig. 9 shows the 66-kv. transmission system of the Atlantic City Electric Company, which consists of a double circuit line from the Deepwater Plant to Woodstown, New Jersey, and another double circuit line from the same point to Atlantic City with other lines running from Woodstown by way of Bridgeton and Seaville to Atlantic City. At Seaville a step-down is made into the 25,000-volt system which runs partly

overhead and partly through many sections of submarine 25,000-volt cable to Ocean City.

Fig. 10 shows the coupling arrangement employed at each of the six points where sets are installed, the coupling being as follows: At Deepwater on the two lines to Atlantic City, inter-circuit; on the two lines to Woodstown, inter-circuit; at Woodstown on the Deepwater lines, inter-circuit and on the lines to Bridgeton and Atlantic City inter-phase; at Bridgeton inter-phase on both lines; at Seaville inter-phase on the two 66-kv. lines plus a bypass into the 25-kv. system around the transformer bank; at Atlantic City inter-circuit on the two Deepwater lines and inter-phase on the Woodstown and Seaville lines; at Ocean City inter-phase on the one 25-kv. line. Of the six sets shown installed five have been in operation for the last three years.

Here again carrier has provided the principal and practically only communication on the entire system and has done it with a reliability unequalled by any other communication that had been obtained on the system until the introduction of carrier. In 1927, during a particularly severe storm along that entire section of the Atlantic coast where all other forms, including all commercial forms of communication in the territory, were very seriously crippled, communication between Atlantic City and the then extreme point, Woodstown, was maintained without the slightest interruption through carrier. It may be of interest that in the section between Seaville and Ocean City there are 2 pieces of 25-kv., 3-conductor submarine cable, aggregating a total of 1200 ft. The communication between Seaville and Ocean City and between Atlantic City and Ocean City is nevertheless of a very high grade, no difficulty having been experienced in getting through all the cable.

Analysis of a Carrier-Current Communication System

In order to give properly the detailed experience with the carrier-current system described, it will be necessary to break up the system into its component parts. It is believed that this will give a better idea of the difficulties encountered and the means adopted for solving them than can be given in any other way.

A carrier-current communication system can be logically divided into three main parts as follows:

(A) Equipment
(B) General channel arrangement
(C) General phases of system.

The equipment (A) can be divided into the following:

1. Coupling system. This embraces—
   (a) The connection to the line
   (b) The coupling proper. The coupling itself can be either in the form of an antenna or in the form of a capacitor, and there are of course many types of capacitors.
   (c) The protective equipment. This includes the disconnecting switches, fuses, drainage coils, spark-gaps, ground switches, and other protective devices on the apparatus side of the coupling equipment used for the purpose of protecting the equipment itself and the operators from the power voltage.
   (d) Tuning equipment. This includes the equipment used for resonating the circuits from the transmitter to the line.
   (e) Carrier traps. These are used for preventing the dissipation of carrier energy into circuits through which it is not desired to communicate, for the purpose of preventing the carrier energy being short-circuited by open branch lines and also for breaking up loop circuits so as to prevent neutralization of signal at the receiving end caused by unequal propagation over the two sides of the transmission loop.
   (f) By-passing equipment. This includes equipment utilized for by-passing a high impedance to carrier such as power transformer, power reactor, etc.
   (g) Lead-in conductors.
2. Transmitting system. This embraces—
   (a) Frequency control. By this is meant the master oscillator circuit.
   (b) Speech amplifier. This consists of the amplifying equipment used to raise the voice signal for input to the modulation system.
   (c) Modulation system.
   (d) Power amplifier system. By this is meant the circuits used to amplify the modulated signal for input and transmission to the line.
   (e) Transmitter blocking system. This is, of course, non-existent in the case of a two-frequency system. In the case of the single frequency system it is utilized for blocking the transmitter output except when the particular station actually does the speaking.
   (f) Signaling system. This consists particularly of the relay equipment and modulating equipment used for calling other stations.
3. Receiving system. This embraces the following:
   (a) Calling system. This includes the equipment used for receiving calling signals from distant stations and translating them into audible signals.
   (b) Tuning and selective system. This includes tuning and amplifying circuits used to select the proper carrier frequency and deliver it to the de-modulation system.
   (c) De-modulation system.
   (d) Audio amplifying system.
   (e) Extension system. This includes the equipment necessary to provide wire line extensions to the equipment. In some cases

these extensions may have to be several miles in length. An actual experience will be cited in connection with some very long extensions.

4. Power supply system for transmitter and receiver. This includes:
   (a) The supply for all the filaments.
   (b) The grid biasing supply.
   (c) Plate supply.
   (d) Control relay supply.

B. General channel arrangement. This can in turn be subdivided into the following:

1. Zoning. As either the system of transmission or the system of communication on a definite transmission system grows, and the carrier installations grow, it is of necessity found desirable to limit the geographical spread of the number of stations on any one channel, which means that a series of channels has to be established. In cases such as the system cited, where the principal dispatching functions are carried on from a number of points, this would logically result in certain zones that are more or less independent of each other.
2. Inter-zoning. As long as the system is a unit system, inter-zone communication will be found necessary under certain conditions. The feasibility of maintaining these zones will be dependent upon clearness, sharpness of tuning, attenuation, and similar questions, and these will be discussed.

C. General phases. Under this can be included the following items:

1. Cost of installations.
2. Maintenance; that is, maintenance considered both from the standpoint of extent and cost.
3. Extent of traffic and ability to handle.
4. Safety.

Coupling System Experience

Before the development of coupling capacitors a number of installations of two-wire antenna coupling, such as is shown schematically in Fig. 11, was installed on the system of the American Gas and Electric Company. These antenna couplings functioned with fair success. However, they were subject to several difficulties and had several objections.

It was found that the tuning of the coupling system varied considerably with changes in weather conditions. In wet weather the volume of received speech was considerably reduced. This was attributed to the change in capacity values of the coupling and to the leakage from the insulator supporting the antenna. On account of the nature of the coupling capacity secured by antenna coupling, the antenna coupling systems gave a much sharper tuning of the output circuit and therefore changes in the value of the antenna capacity caused a very great change in the output circuit tuning.

At the time the transmission towers were installed, no thought was given to providing additional strength so as to support antenna coupling wires without reducing the safety factor. The towers were designed for two circuits and one ground wire. Later developments required the installation of another ground wire so that if antenna coupling had been continued it would have been necessary to place three more conductors on the structure than the structures were originally designed for or sacrifice either the ground wire or the factor of

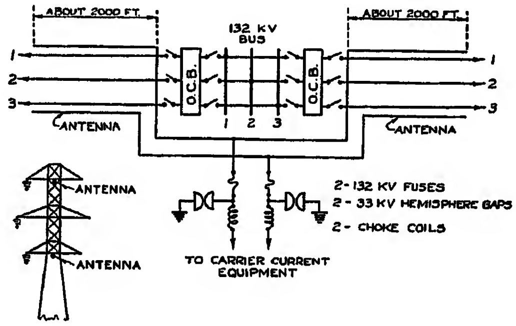


Fig. 11—Schematic Diagram of an Antenna Coupling Installation

safety. Again difficulties were encountered due to the rigid requirements of the railroad companies covering the method of supporting conductors across their rights-of-way.

On the antenna coupling systems which were installed, the same size and kind of conductors were used as for the power conductors in order to secure the same sag and the same deflection under wind. Even with these precautions, as will be noted from the diagram, the installation of the antenna conductors in line with the

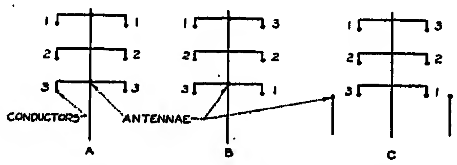


Fig. 12—Schematic Diagram of Antenna Coupling Arrangements

vertical center line of the towers so reduced the clearance between the power conductors as to run the danger of their falling upon the antennas if the power conductors should break. One case of this trouble was experienced at the Canton substation in the year 1924, when the power conductors came down across the antenna coupling wires. The antenna coupling wires were protected by 132-kv. fuses, which were installed very close to the transmitting equipment immediately outside the building. While the fuses blew nevertheless a considerable amount of damage was done to the carrier telephone set.

Another difficulty experienced in the use of antenna coupling is brought about by the asymmetrical stringing of double circuit lines. Referring to Fig. 12, a two-wire antenna system is shown at *A* coupled to a double circuit line strung symmetrically. This method produces a satisfactory coupling to the transmission line. A double circuit line strung asymmetrically is shown at *B* with the antenna conductors located at the same place as at *A*. It will be noted that both the upper and lower antenna conductors are equally coupled to phases 1 and 3, thereby causing the coupling to be neutralized and to be of no effect.

Our double circuit transmission lines are now all strung asymmetrically in order to take advantage of the reduction in reactance brought about by this method. It will therefore be seen that antenna coupling cannot be used on double circuit lines strung as shown at *B* and it would be necessary to adopt a method of supporting the antenna conductors, as shown at *C*, in order to secure an effective coupling to the line.

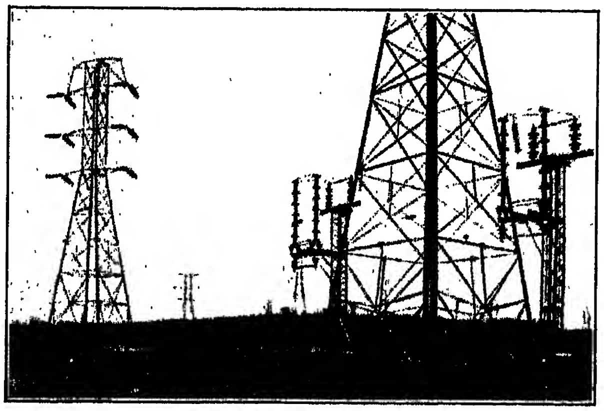


FIG. 13—MICA DIELECTRIC CAPACITOR INSTALLATION, OHIO POWER CO., CANTON, OHIO

All of the above considerations contributed to the adoption of high-voltage capacitors for coupling as soon as they were developed. The first installation of coupling capacitors on the American Gas and Electric Company lines was made on the 132-kv. double circuit line from Canton to Philo, Ohio, in the year 1925. This installation consisted of two 132-kv. assemblies at Canton and two at Philo connected inter-circuit to the double circuit line. See Fig. 13, showing the installation at Canton. The capacitors were of the mica dielectric type. Mica was chosen because at that time it was the only thing available. Twelve units were used for each 132-kv. assembly, each unit having a normal operating voltage rating of 22 kv. and a capacity of 0.003 μ f. Six units were connected in series and two series of six units in multiple to produce a 132-kv. assembly having an over-all capacity of 0.001 μ f.

These four original 132-kv. assemblies have continued to operate without any trouble whatsoever.

In making the first few installations of capacitors on the 132-kv. system, high-voltage disconnecting switches and choke coils were installed between the line and the capacitors. The choke coils were installed with the idea of protecting the capacitors from voltage surges and the disconnecting switches were installed so as to facilitate the taking of the capacitors out of service for maintenance and repairs, or to provide a quick means of clearing the capacitors from the line if they should break down, very little at that time being known concerning the reliability of such devices.

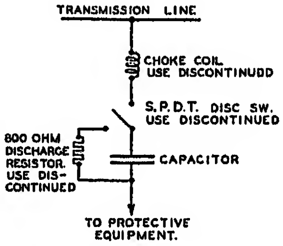


FIG. 14—PROTECTIVE AND SAFETY FEATURES USED ON EARLY CAPACITOR INSTALLATIONS

In the first installations a safety device was installed as shown by Fig. 14. This consisted of an 800-ohm resistance so connected that when the high-voltage disconnecting switch was open its blade would come in contact with one terminal of the resistance, the other terminal of the resistance being connected to the low side terminal of the capacitor, thereby discharging the capacitor through the resistance and rendering the capacitor safe to work on.

The disconnecting switches, choke coils, and protective resistance considerably increased the cost of the capacitor installations. As more experience was secured with the capacitors and confidence in their reliability obtained, the use of switches for disconnecting the capacitors from the line was discontinued and the capacitors connected solidly to the line.

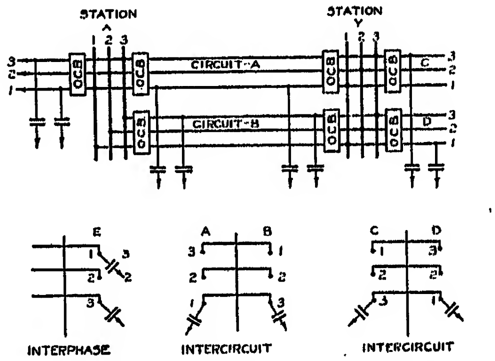


FIG. 15—INTER-PHASE AND INTER-CIRCUIT COUPLING ARRANGEMENTS

Fig. 15 shows schematically systems of inter-phase and inter-circuit couplings by means of capacitors. The coupling to line *E* is an inter-phase coupling. The coupling to lines *A* and *B* at each of their ends is made

by inter-circuit coupling, the two lines being strung asymmetrically on the transmission towers. The same holds true for circuits *C* and *D*. Although the relative location of the right and left hand circuits on the two towers supporting the last two groups of lines is interchanged, no interference results in the method of coupling employed, the circuit being a perfectly complete carrier-current circuit. The method of inter-circuit coupling offers particular advantages in economy where a double circuit line is employed, and while it is not fully as effective under all emergency conditions as full inter-phase coupling on every circuit, nevertheless it results in so much reduction of cost that the slight inconvenience that results sometimes is more than compensated for by this lesser cost. In spite of its extensive use on the system, there has practically never arisen a situation where communication was interfered with to any appreciable extent as a result of one of the two circuits going out, the general experience being that if one of two coupling points provided at each of the two terminals of a particular line remained coupled, communication could be carried on over the line.

As pointed out, the first capacitors were of mica. The principal reason for this was that they were the only ones obtainable. Even here it was necessary to carry on considerable cooperative work with the manufacturers before a successful unit was developed. However, the experience that had been obtained over many years in the operation of a power system with solid dielectrics suggested the necessity for great caution in proceeding with the extensive use of mica for very high voltages. The development of carrier communication had resulted in a number of other manufacturers taking up the capacitor problem, so that within a short time from the first installation on the A. G. & E. system, there were available on the market at least three other types of capacitors and one other make of mica capacitor. A series of very extensive tests made of all these units, including elaborate impulse tests, fully substantiated the fears entertained with regard to mica as a result of general experience. Accordingly very few mica installations after that date were made on the 132-kv. system, the principal installation being confined to the following types:

(a) A cable type capacitor. This has been described before the Institute.[31]

(b) A modification of the original cable type capacitor, combining a current transformer feature with the capacitor. A typical installation of the first of these is shown in Fig. 16. It will be seen that the unit is connected directly to the line, the fuses indicated in the photograph being on the equipment side of the capacitor. A typical installation showing a cable capacitor with current transformer feature is shown in Fig. 17. The current transformer secondary can be seen very clearly in the bottom portion of the cable loop of the left-hand side capacitor. The equipment shown between the two capacitors contains the protective equipment. Details of this protective equipment showing its connection to the capacitors, as well as the details of the line tuning equipment, are shown in Figs. 18 and 19, respectively.

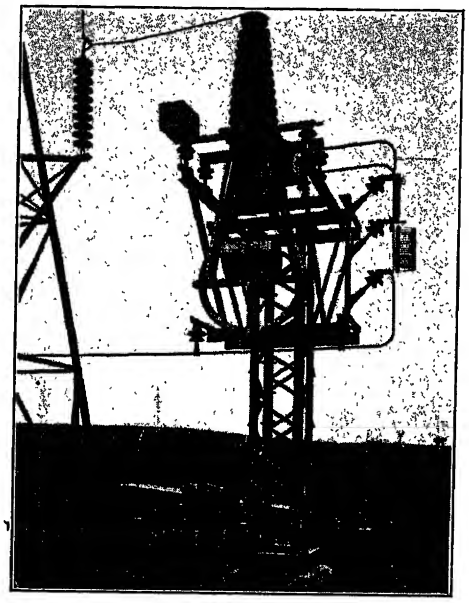


Fig. 16—General Electric Co. Cable Type Capacitor Installation, Ohio Power Co., Canton, Ohio

In Fig. 20 is shown a diagrammatic sketch of an arrangement in which a combination of current transformers and coupling capacitors is installed on two lines connected to a high-tension bus. It will be seen that the existence of the current transformers has practically no effect on the method in which the capacitor itself is used and that the same connection to the carrier-current sets and to the lines is employed as in the straight capacitor.

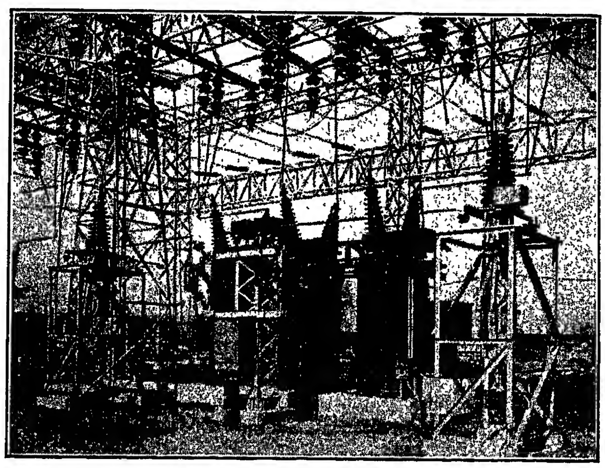


Fig. 17—General Electric Co. Combined 132-Kv. Cable Capacitors and Current Transformers, Indiana General Service Co., Marion, Ind.

In connection with these current transformer com-

bination capacitors, it may be of interest to give some experience with the accuracy obtained from the two-stage current transformers. Table II gives the accuracy characteristics of these transformers and it will be noted that the accuracy is comparable to the accuracy obtained with standard definite wound high-voltage transformers. In fact, the accuracy secured is of a higher order and is not subject to change on account of variable instrument burdens to the extent met with in definite wound transformers.

TABLE II

RATIO AND PHASE ANGLE CHARACTERISTICS OF A 150-AMPERE, 132,000-VOLT, 2-STAGE CURRENT TRANSFORMER WITH 2 TURN PRIMARY COMBINED WITH A CABLE CAPACITOR

Secondary amperes	Ratio correction factor	Phase angle in minutes
Secondary burden = 33.3 volt amperes at 0.94 power factor; Tertiary burden = 15.0 volt amperes at 0.98 power factor		
0.5	0.9985	+4
1.0	0.9986	+3
2.0	0.9987	+3
3.0	0.9987	+2
4.0	0.9987	+2
5.0	0.9987	+2
Secondary burden = 10.9 volt amperes at 0.90 power factor; Tertiary burden = 10.7 volt amperes at 0.91 power factor		
0.5	0.9985	−1
1.0	0.9986	−1
2.0	0.9987	−1
3.0	0.9987	−1
4.0	0.9987	−1
5.0	0.9987	−1

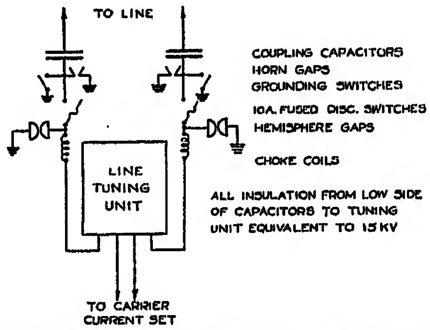


FIG. 18—SCHEMATIC DIAGRAM OF CAPACITOR COUPLING PROTECTIVE SYSTEM

The experience obtained with these cable type capacitors, whether of the straight type or combination type, has been uniformly successful and covers now a period of three years. In that time there has not been a single break-down, although there are installed at the present time approximately 80 of the units on the 132-kv. system. There has been some trouble experienced with the sylphon bellows used at first on the bushing, the principal difficulty being the leakage of oil, but these were replaced with expansion drums similar to the construction employed in high-voltage cable work and the difficulty has been entirely eliminated.

In Fig. 21 is shown an installation of the so-called tank type capacitors on a 132-kv. bus at Philo. These consist essentially of two metallic cylinders forming the capacitors plates with oil as a dielectric, the oil being, of course, broken up by a series of insulating cylinders. It was believed, and the tests carried out fully proved this, that while the cable type capacitor offered a

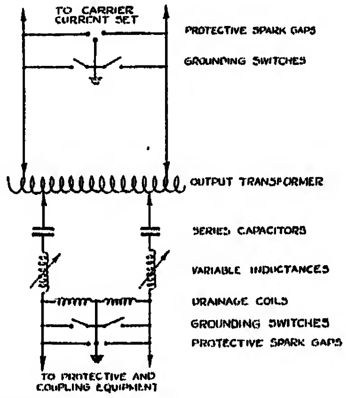


FIG. 19—SCHEMATIC CIRCUIT DIAGRAM OF LINE TUNING UNIT

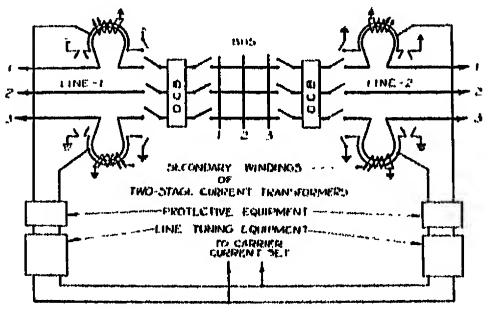


FIG. 20—INTER-PHASE COUPLING WITH COMBINED CAPACITORS AND CURRENT TRANSFORMERS

FIG. 21—GENERAL ELECTRIC CO. 132-KV. TANK TYPE CAPACITORS, OHIO POWER CO., PHILO, OHIO

piece of equipment sufficiently adequate for all purposes, particularly from an impulse strength standpoint, experience with even more reliable equipment would be desirable in case some unlooked for operating experience

developed with the cable type capacitors. A number of installations of this tank type capacitor was therefore made. No trouble of any kind was experienced with them and the maintenance work on them has been confined strictly to such routine work as inspection for leaks, painting, etc.

In Fig. 22 is shown an installation of a combination oil and porcelain capacitor, some of which were made on the 132-kv. system in connection with Western Electric sets. These capacitors consisted of a series of porcelain shells with metallic sheathing on the inside and outside which formed the capacitor unit. A complete unit consisted of two such shells, one within the other connected in series, and a group of these was built up between two metallic cradles, one near the bottom and the other near the top of the tank which acted as a paralleling medium for the various units. A number of these individual units with an individual capacity of approximately 0.0003 μ f. was built up to give a total capacity of 0.007 μ f. This large capacity was

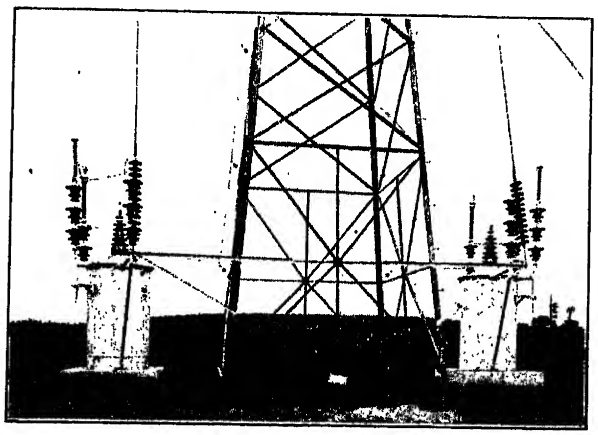


FIG. 22—OHIO BRASS CO., 132-KV. TANK TYPE CAPACITORS, OHIO POWER CO., CANTON, OHIO

felt by the carrier-current manufacturers' engineers to be highly desirable, apparently in view of the low power input employed on these sets. The capacity of all other capacitors employed on the 132 system has never been in excess of the maximum 0.001 μ f. and the experience obtained with that capacity has shown that under all conditions it has been more than adequate to provide adequate couplings.

The capacitors shown in Fig. 22 were originally equipped with series resistors on the high side. It was found impossible, however, to maintain these resistors in service owing to the large number of failures that occurred when trouble was experienced with the capacitor itself. A total of four separate failures on two capacitors was experienced and, as a result of that, the use of this particular type of capacitor was abandoned.

It was replaced with the capacitor shown in Fig. 23 which shows an installation at Cabin Creek. This consists of a series of porcelain shells electroplated on the inside and on the outside, the porcelain shell being approximately one inch thick. Regular insulator type of petticoats are employed at the bottoms to give the necessary leakage distance for outdoor use. Each of these units has a capacity of 0.001 μ f. and a combination such as shown in Fig. 23 of four of these units in

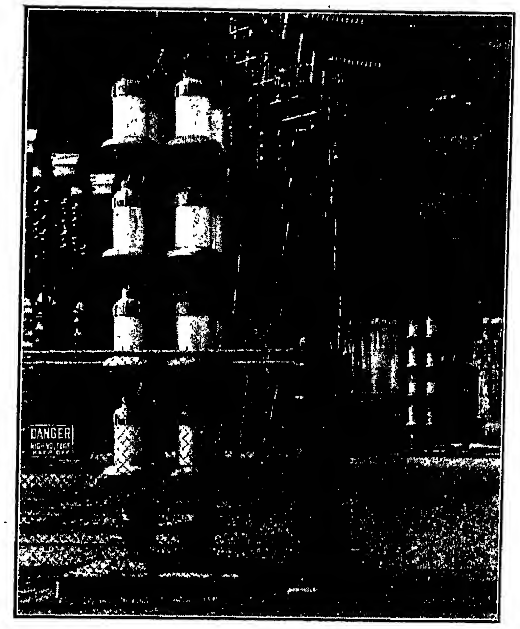


FIG. 23—OHIO BRASS CO. 132-KV. DRY TYPE PORCELAIN CAPACITOR ASSEMBLIES, APPALACHIAN ELECTRIC POWER CO., CABIN CREEK, W. VA.

parallel and four in series, gives a capacity of 0.001 μ f. at 132 kv. Like the cable capacitors, they are connected solidly to the bus. The maximum length of service on any one of these units has been approximately a year. To date the operating experience has been entirely satisfactory.

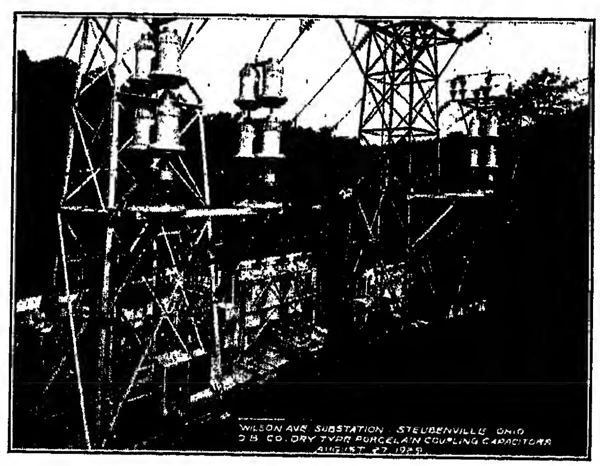


FIG. 24—OHIO BRASS CO. 66-KV. DRY TYPE PORCELAIN CAPACITOR ASSEMBLIES, OHIO POWER CO., STEUBENVILLE, OHIO

An installation of the same type of unit consisting of a two by two combination, is shown in Fig. 24. This is on a 66,000-volt installation which has been in service

approximately six months with entirely satisfactory results to date.

A 132-kv. installation of the mica capacitors is shown in Fig. 13. As pointed out before, subsequent to the insulation tests, particularly the impulse tests carried out on various makes of capacitors, the use of this equipment on the 132-kv. system was entirely abandoned. Quite a number of points that had previously had installations of mica made on them, were changed to some of the other types enumerated, where it was found possible to utilize the mica units at lower voltages. Nevertheless, in spite of the reduction of coupling points, in the past three years there have been five cases of distinct failures or break-down of mica capacitors on the 132-kv. system and with the exception of the failures of the combination porcelain and oil capacitor previously referred to, these have been the only failures.

The use of mica on low-voltage systems such as

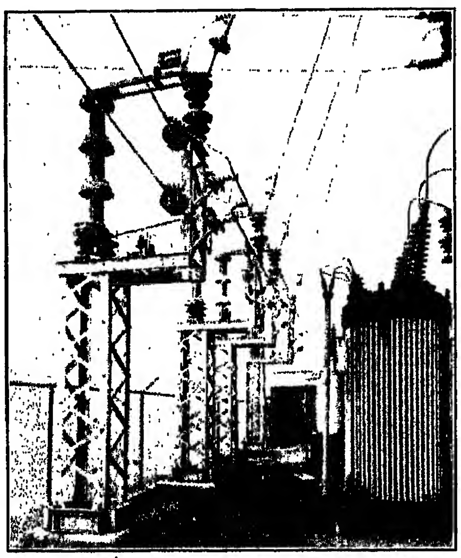


FIG. 25—DUBILIER 66-KV. MICA CAPACITOR ASSEMBLIES, OHIO POWER CO., CROOKSVILLE, OHIO

66,000 volts and below, has been continued and is being employed on the system today. A typical installation at 66,000 volts is shown in Fig. 25. Extensive experience has been obtained in the past five years with mica on circuits of 66,000, 44,000, 33,000, 27,500, and 25,000 volts and not a single case of failure was experienced. It should be noted, however, that in the low voltages, such as 25,000 volts and 33,000 volts, no fewer than two single 22-kv. rated units were ever employed in series.

In view of all the above it is believed that the coupling problem has very definitely been solved and that equipment is available today with as high a factor of safety, if not higher, (since the capacitor with a capacity of 0.001 μ f. has an appreciable amount of self-protection) than is obtained in all the other links of the transmission chain. Some progress can still be made in the direction of reducing costs, but even this, it is felt, is very promising for the future.

PROTECTIVE SYSTEM

As mentioned previously, on the first installations of coupling capacitors, disconnecting switches and choke coils were installed between the transmission line and the high side terminals of the capacitors. On all installations made within the past three years, no disconnecting switches or choke coils have been used, the capacitors being tapped directly to the transmission circuit and treated from an insulation standpoint similar to that of an insulator dependent solely upon the automatic breaker protection of the line to clear the line if a faulty capacitor should develop.

On the first installation of capacitors where high side disconnecting switches were employed, it was thought desirable from a safety standpoint to provide a means of discharging the capacitor after it had been disconnected from the line. Fig. 14 shows schematically how this was done by providing a resistance of the order of 800 ohms in the discharge circuit. After the practise of connecting capacitors directly to the line was adopted, the use of these discharge resistors was discontinued.

Fig. 18 shows the standard protective scheme which is employed on the equipment side of the capacitors for protecting the equipment and operators. This is self-explanatory, although it might be well to call attention to the relative location in the circuit of the fuses, choke coils, and sphere gaps, the object being, of course, to make sure that under the discharge of the gap, fuse action is obtained at all times. Supplementary protection is provided by the 60-cycle drainage coils located in the line tuning units. The practise of placing a two-pole telephone type fused disconnecting switch in series with the lead-in conductors close to the carrier equipment, has also been followed consistently.

It will be noted that the drainage coils used to drain the 60-cycle exciting current of the capacitors to ground are located in the line tuning unit. Fig. 19. The capacitors obtain their ground point through the drainage coils. If, therefore, the sphere-gaps act to blow the fuse, the capacitors will discharge over the horn gaps in Fig. 18, and the passage of the discharge current across the horn-gaps will result of course in a high-frequency disturbance over the entire system. This can be remedied by the throwing in of the ground switch, shown in the diagram, or by re-fusing of the fuse. It is planned, however, to change the position of the drainage coils to the line side of the fuses so as to eliminate this trouble.

The protective system outlined has in no case failed to function as contemplated or failed to take care of any situation that has arisen on the power end. In other words, it has acted entirely satisfactorily during the whole period covered.

Lead-In Conductors

In making the first installation of carrier sets, the conductors connecting the antenna coupling wires or coupling capacitors with the carrier sets were run overhead, a nominal insulation of 33-kv. being used. In placing these lead-in conductors overhead, it was necessary to support them on the steel framework of the station structures by means of pillar type insulators, using copper tubing. It was also necessary to provide towers to support these conductors from station structure to the station building. These overhead lead-in conductors were very costly to install and introduced additional hazards, due to possibility of contact with power conductors. They were more or less unsightly and were many times found to be in the way of future construction.

Within the last two years, practically all of the lead-in conductors for new installations have been placed under ground, and also a number of the overhead lead-in conductors of earlier installations are now being placed under ground.

The lead-in conductors now being used for underground services consists of a two conductor No. 8 A. W. C. cable insulated for 2500-volt service with Kerite or 30 per cent para rubber, lead covered and steel armored. This cable is buried in the ground without any additional protection. The cost of an underground lead-in installation using this cable is approximately one-half the cost of an overhead installation.

At the time we first started to use underground cable lead-ins, the manufacturers would not guarantee satisfactory operation with cables greater than 600-ft. in length. Recently underground cable lead-in installations made at several of the larger stations required the use of cable to the extent of over 1000 ft. in length. After these installations were put into operation trouble was experienced in the form of distortion of received signals, which was attributed to the long underground lead-ins. The manufacturer immediately undertook a study to determine the means to secure satisfactory operation with long cable lead-ins, the result of which study has been the development of an impedance matching transformer. This transformer will be used as follows: A length of lead-in cable will be installed from the carrier set to a distribution point located in the outdoor switching yard, approximately equi-distant from the various sets of coupling capacitors installed on the transmission line. At this distribution point one winding of the impedance matching transformer will be connected to the high-frequency conductors from the set, and underground branch lines will be run from taps in the second winding of the transformer to the various line-tuning units. One of these impedance matching transformers will be used in each line-tuning unit to replace the air-core auto transformers generally used in these units where overhead lead-in conductors are employed. Laboratory tests indicate that the use of these impedance matching transformers will enable the use of underground lead-in conductors of any length which may be required in any commercial installation.

Tuning of Couplings and By-Passing

Fig. 19 shows the schematic circuit of a line tuning unit which is connected between the carrier set and the coupling equipment for the purpose of resonating the coupling circuit to the frequency used.

In earlier equipments where overhead lead-in conductors were used, the tuning equipment for resonating the coupling was included in the transmitting equipment. In the later sets the lead-in conductors are treated as a high-frequency transmission line and the tuning done directly at the coupling. The line tuning unit consists essentially of two variable inductances in the form of variometers. Two capacitors are provided for the introduction of either series of shunt capacity in the tuning circuit. An air-core auto transformer is also included for the purpose of stepping up or stepping down the carrier voltage.

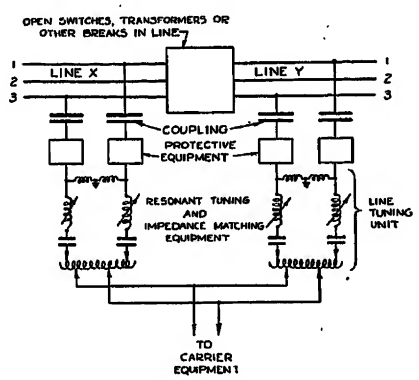


Fig. 26—Schematic Diagram of By-Passing with Line Tuning Units

Fig. 26 shows two line tuning units connected to the transmission lines X and Y, which lines are isolated from a carrier-frequency standpoint due to open switches or intervening transformers. When both of these line tuning units are tuned to the same carrier frequency, it will be noted that a tuned path for that carrier frequency is provided around the break in the line. At the same time, when both line tuning units are tuned to the same frequency this frequency may be transmitted into both lines, or when the two line tuning units are tuned to different frequencies they serve the purpose of directing each frequency into its proper line.

In some of the earlier installations the couplings to each line of a number of lines were not separately tuned, but the low side terminals of all the couplings were connected in parallel and the combined coupling to all the lines tuned by means of one line tuning unit. This scheme of tuning was found to work satisfactorily, and in most cases fairly successful by-passing was secured. However, by tuning each coupling separately,

much more efficient by-passing is secured and it is felt that the additional cost of tuning each coupling separately is justified by the greater reliability of by-passing secured.

Fig. 27 shows schematically the carrier telephone installations on the systems of the Pennsylvania Power

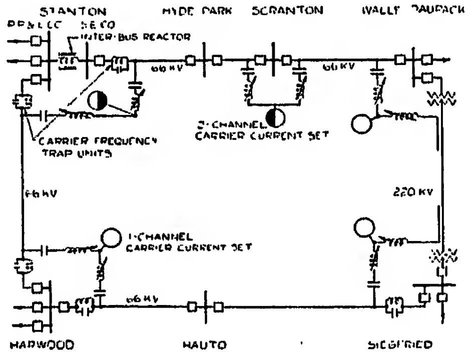


Fig. 27—Schematic Diagram of Coupling, Tuning, and By-Passing on Interconnected Systems of Scranton Electric Co. and Pennsylvania Power and Light Co.

and Light Company and the Scranton Electric Company in Pennsylvania.

At the Stanton Plant the 66-kv. buses of the two companies are interconnected by a reactor tie. Communication was desired between Harwood and Wallenpaupack by two routes, one route by way of Siegfried and one route by way of Stanton Plant. This has been accomplished by installing a by-passing system at Stanton Plant around the reactor. Carrier-frequency trap units, as shown in Fig. 28, are installed in the feeders used for the carrier channel to confine the carrier energy to the desired circuits and exclude the carrier energy from other circuits through which communication is not desired and in which the energy would otherwise be wasted. These trap units are also installed at Harwood and Siegfried for preventing loss of carrier energy in other circuits.

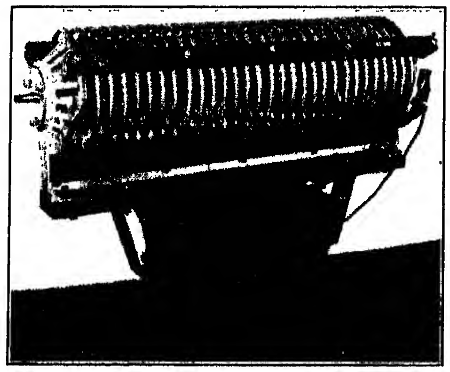
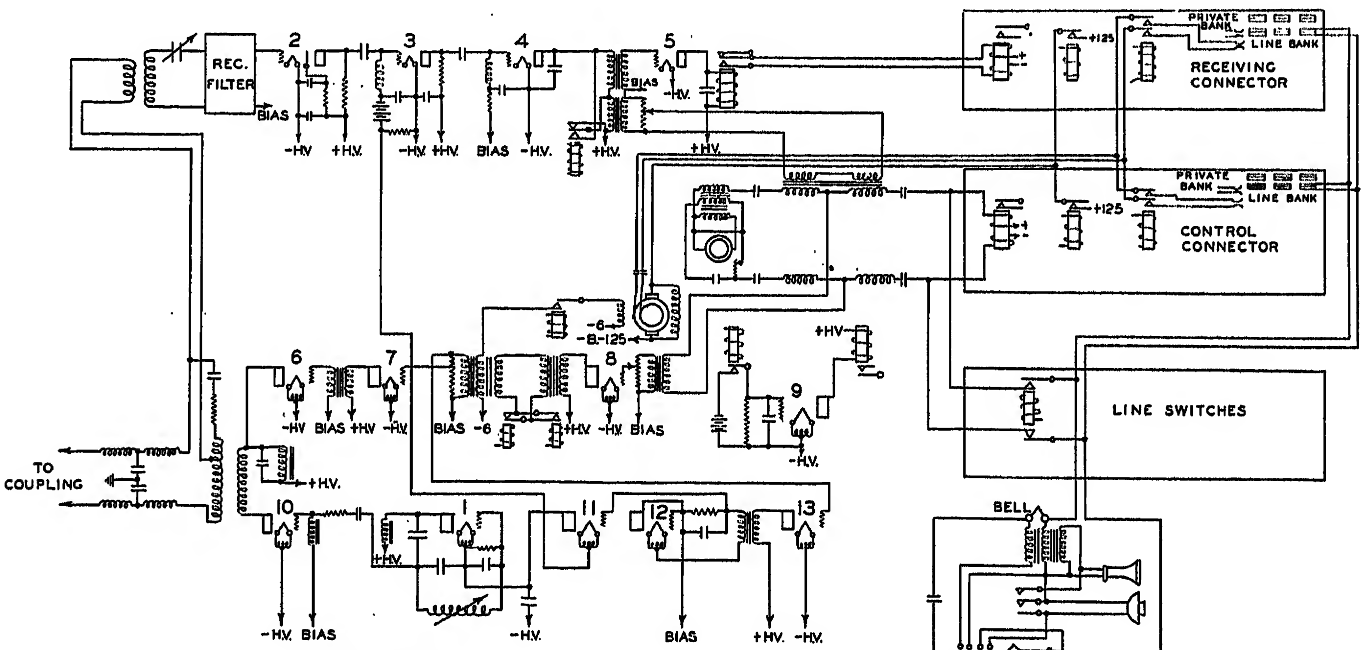


Fig. 28—Tuned Carrier-Current Trap Unit

These trap units consist of a 400-ampere choke coil, having an inductance of approximately 70 microhenries with an adjustable capacitance in shunt, the capacitance being arranged so that the unit may be tuned to resonance at any frequency from 50 to 150 kilocycles.

These carrier trap units are also suitable for blocking carrier energy out of stub feeders where the length of



TUBE LEGEND

1. MASTER OSCILLATOR
2. SCREEN GRID R.F. AMPLIFIER
3. PROTECTIVE & VOLUME CONTROL TUBE
4. DETECTOR
5. CALL AMPLIFIER
6. 50 WATT MODULATOR
7. SPEECH AMPLIFIER
8. LINE AMPLIFIER
9. CALL TIMING
10. 50 WATT POWER AMPLIFIER
11. CONTROL TUBE
12. CONTROL RECTIFIER
13. CONTROL AMPLIFIER.

Fig. 29—Schematic Circuit Diagram of a 50-Watt Primary Set, Type KCA-1, General Electric Co.

the feeders is such as to absorb an undue amount of the carrier energy. They are also suitable for breaking up loop transmission circuits and directing the flow of carrier energy around the desired portion of the loop so as to prevent reflection or neutralization of the signal energy. In connection with the 132-kv. system, we have not yet found it necessary to employ trap units for the two last-mentioned purposes, although there is little doubt but what these applications will be required in the future.

Transmitting System Experience

Fig. 29 shows a simplified schematic diagram of the circuits of one of the latest type of primary 50-watt sets, known as a type KCA-1 set. This set uses a 7.5-watt master oscillator (1) in a Colpitts circuit driving 50-watt power amplifier. (10) A 7.5-watt line amplifier (8) and a a 7.5-watt speech amplifier (7) are used to build up the voice energy for input to a 50-watt modulating tube (6) which modulates the carrier energy in a Heising modulating circuit. The modulated carrier energy is delivered to the coupling system through a two winding radio frequency output transformer.

The operation of the oscillator blocking circuit used to secure duplex, single-frequency operation is as follows: A 7.5-watt audio amplifier (13) designated control amplifier receives the audio signal from the line amplifier (8) and amplifies the audio signal which is then impressed upon the control rectifier, (12) which is a 7.5-watt tube functioning as a half wave rectifier, rejecting one-half of the amplified audio voltage received from the control amplifier. The rectified pulsating d-c. voltage output of the control rectifier, (12) after being smoothed out, is impressed upon the grid of the control tube. (11) The grid of the control tube during reception periods is normally biased negative to cut-off. The filament return circuits of the master oscillator is obtained through the plate-filament circuit of the control tube. When the plate-filament circuit of the control is open or cut off by the high negative grid bias on the control tube grid, the plate circuit of the master oscillator is open circuited, preventing the master oscillator from oscillating. When a voice signal is impressed on the microphone, the control amplifier and control rectifier act to place a high positive bias on the grid of the control tube overcoming the normal high negative bias of its grid. This positive bias on the control tube grid reduces the plate-filament impedance of the control tube, providing a low impedance return path for the plate-filament circuit of the master oscillator, allowing plate current to flow to the oscillator and permitting the oscillator to function.

This blocking system is quite simple and on the later models of sets works highly satisfactorily. In the earlier sets the action of the blocking system could usually be heard in the receiver as a click, but in the later models of sets this does not exist, and when properly adjusted no evidence is given to the speaker of the action of the blocking system.

The various bias voltages for the transmitting tubes are secured from taps taken from a resistor shunted across the output of a 125-volt d-c. generator which is one of the units of the 4-unit motor generator set to be referred to later.

Signaling is accomplished by introducing into the grid circuit of the speech amplifier a 300-cycle a-c. voltage produced by a small rotary converter supplied from the 125 voltage station storage battery.

The transmitting system as a whole is quite simple, and the performance has shown this up; practically no trouble has been experienced with it.

Receiving System Experience

In the earlier models the tuning system for selecting the desired frequency consisted of two simple coupled tuned circuits, feeding a non-regenerative detector. This simple tuning scheme was sufficient at first but as the number of stations on the system and the number of

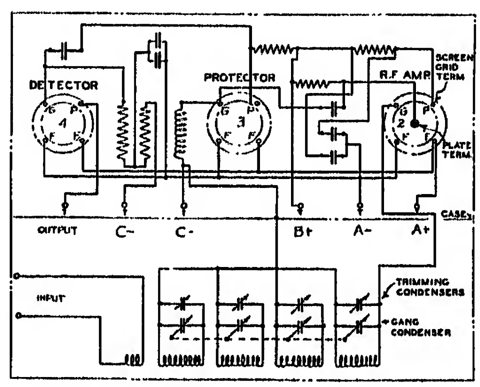


Fig. 30—Schematic Circuit Diagram of Selectivity Filter

channels increased, it was found that the simple tuning system was not sufficiently selective, with the result that stations operating on other frequencies were able to interfere with the reception of desired signals. This brought about the development of receiving systems having higher selectivity characteristics. Fig. 30 is a schematic diagram of the circuits of this filter. A high degree of selectivity is secured by the four coupled tuned circuits, the last one of which feeds into a 4-element screen grid tube (2) used as a radio frequency amplifier. This radio frequency amplifier feeds into a non-regenerative detector.(4)

The middle tube is a protector tube (3) which is used to block the receiving circuits automatically during transmission periods. During receiving periods the grid of the protector tube has a negative bias giving the tube a high filament-plate impedance. During transmission periods a positive bias is used to overcome the normal negative bias, reducing the filament-plate impedance of the tube, thereby short-circuiting the input to the detector, resulting in blocking of the receiving circuit.

Reception is secured directly out of the detector circuit without the use of audio amplification. This results in an exceptionally clear signal. One stage of audio amplification (5) fed by the detector is used for operating the calling relays. Automatic selective telephone switching equipment is provided for connecting the extension lines to the transmitting and receiving circuits, provision being incorporated for a maximum of 10 two-wire telephone extensions.

The carrier telephone system is being used primarily for dispatching and very little other communication is allowed to go over it. For this reason, very few cases have come up where extensions to the carrier equipment have been required. One such extension, however, is in operation at Canton, Ohio, between the substation and the main office, about two miles distant. This extension is made over a pair of telephone wires in a cable circuit leased from the telephone company. The extension has operated entirely satisfactorily.

Of all of the component parts of the carrier communication system, the signaling system has probably given more trouble than any of the others. The signaling is, however, a very important part of the system, calling being obviously a prerequisite to carrying on communications. In the later models the signaling system has been very greatly improved, and within the last two years considerably less trouble has been caused by it.

Realizing the extreme importance of the signaling system, we made arrangements that all stations be provided with supplementary loud speaker calling. This has been found to be of great value, particularly during times when the system in general is in distress, as the loud speakers at all stations can be connected and instantaneous voice calling used. It takes an appreciable length of time to operate the dialing system to call a station, and during times of system trouble the time of the operators is at a premium and the loud speaker calling saves considerable time and also enables the dispatching operator to be in communication at all times during the trouble with all the other stations on the channel, and enables all other stations on the channel to keep informed regarding the status of the system trouble.

Power Supply

Fig. 31 shows schematically the four-unit motor generator set used to supply the several forms of current and voltage for the 50-watt primary sets. The d-c. motor of the unit receives its supply from the station storage battery. This four-unit set operates only during periods of transmission. In the same diagram is shown schematically the full wave tungar charger used to trickle charge the 6-volt storage battery which supplies the filaments of the receiving tubes. The filaments of the transmitting tubes are supplied from the alternator of the four-unit set. The plate supply for the receiver tubes is taken directly from the station storage battery. This entire power supply system has been found practical and reliable.

In the earlier sets the 6-volt filament battery was trickle charged by means of a motor generator set. This required that the motor generator set operate continuously. Considerable trouble was experienced in maintaining these motor generator sets in operating condition due to their continuous service. All of the trickle charging motor generator sets have now been replaced with tungar chargers and the experience so far has been that these chargers require practically no maintenance.

In addition to the 6-volt filament battery a small 24-cell, 48-volt battery, which is not shown on the diagram, is used to supply current for operating the various control relays in the set. This battery is trickle charged from the 125-volt station storage battery through a variable resistor. In the earlier sets the control relay supply was taken from the 6-volt battery used for the filaments. This low voltage is not satisfactory for relay work and considerable trouble has been experienced due to dirty or oxidized contacts offering a relatively high resistance to the 6-volt supply. Since the adoption of the 48-volt control battery this trouble has practically ceased and very little maintenance work is now required to keep the various relay contacts in good operating condition.

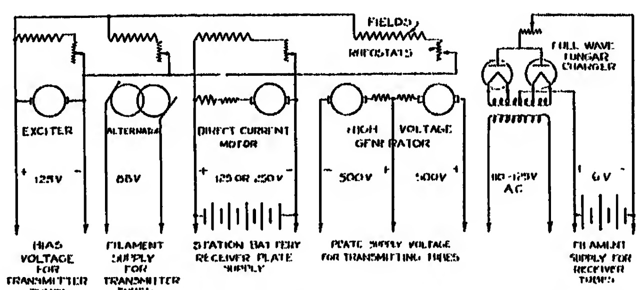


Fig. 31—Schematic Diagram of Four-Unit Power Supply Setf or Type KCA-1 Primary Set

The following general troubles have been experienced with the 4-unit motor generator sets, particularly the sets furnished with the earlier models of equipments: Oil from the bearings found its way on to the commutators, which combined with the carbon dust from the brushes and formed a high-resistance short circuit between the commutator bars. These short circuits between the bars were of such high resistance that they would probably not have any effect upon the satisfactory operation of a generator used for supplying power for commercial purposes. However, these short circuits produced very noticeable fluctuations or ripples in the output of the generators, which seriously interfered with the quality of speech transmitted by the sets. This trouble has been practically overcome in the later sets by completely redesigning the generators for communication service.

Fig. 32 shows schematically the various rectifiers used to supply the filaments, plates, grids, and control relays of the secondary type of set. The receiver filaments are supplied from a 6-volt storage battery trickle charged by a half-wave tungar rectifier. The relay control circuits receive their supply from a 48-volt storage battery, which is trickle charged from the rectifier used to supply the receiver plates. In order to make this set independent of failure of the a-c. supply a 2-unit motor-alternator is provided. This machine ordinarily stands idle and only comes into use automatically upon the failure of the a-c. supply. Its motor is supplied from the station storage battery and the alternator supplies the a-c. input to the set. One of these secondary sets has been in service for about one year at Rutland, Ohio, (reference Number K-45) with very satisfactory results.

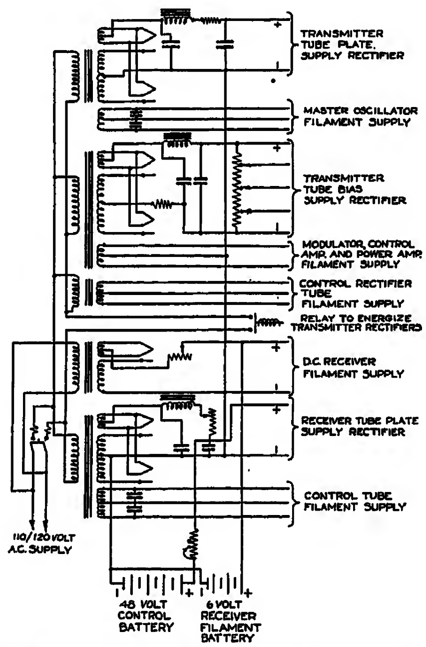


FIG. 32—SCHEMATIC DIAGRAM OF RECTIFIER POWER SUPPLY FOR TYPE KCA-100 SECONDARY SET

ZONING AND INTERZONING

Fig. 33 shows a diagram of the A. G. & E. portion of the 132-kv. system shown in Fig. 4. The diagram not only shows the 132-kv. transmission lines and the various locations of carrier-current sets but also indicates how the various channels have been distributed. As will be seen from the diagram, nine channels are at present utilized (if Toledo is taken into account) on the A. G. & E. system.

These channels are outlined in detail in Table I; the table is, however, more complete and covers the entire 132-kv. system. Thirteen channels are indicated in the table (Toledo not being shown), of which nine are used on the A. G. & E. 132-kv. system.

An examination of Fig. 33 will show very distinctly that Lynchburg, for example, by the very nature of the geographical distance, can have little business with South Bend that could not be cleared up and better taken care of by some other point or somebody else in the system very much closer to Lynchburg. As a matter of fact, Switchback, which is one of the five principal dispatching points previously mentioned, is as far as Lynchburg ever needs to go. In fact, the system set-up is such that if Lynchburg goes farther than Switchback, it becomes a positive nuisance and results in the cluttering up of the system with carrier to the detriment of the carrying on of other business. This is true of a system such as the one shown in Fig. 33, where there is some measure of co-ordination between a group of companies subsidiary to one parent company. Obviously this is more apt to be so where the companies are merely inter-connecting companies, with no other relationship except certain contract relationships between them.

All this was clearly indicated from the very beginning of application of carrier and as the system was extended, the necessity for it became absolutely imperative. As a result the grouping indicated was worked out, taking into account such things as operating relationships of the various points, location of dispatchers, location of interconnection points, amount of business transacted in a certain area, etc. It will be noted that three of the five principal dispatching points have two frequencies, and one of the points (Shelby) has actually

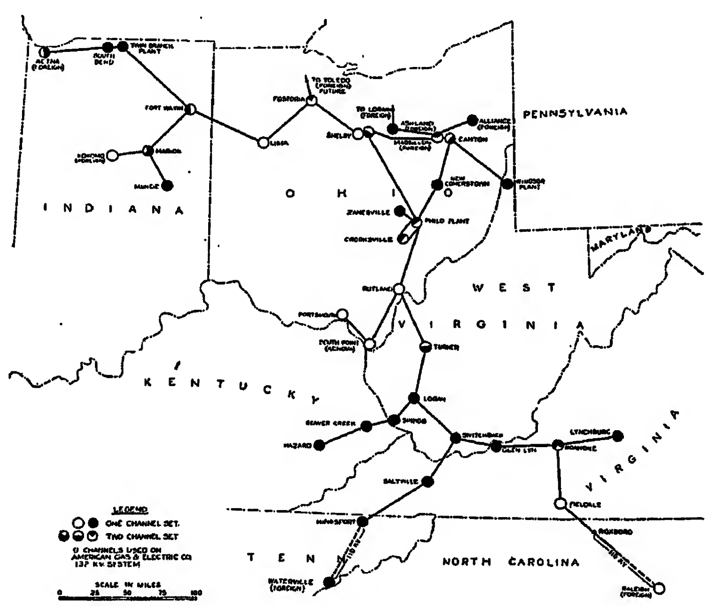


FIG. 33—DIAGRAM SHOWING CARRIER CHANNELS ON AMERICAN GAS AND ELECTRIC CO. 132-KV. SYSTEM

two sets, since three channels are utilized at that station. Where two channels only were found necessary in a station, this was done by a so-called intersystem attachment which consists of nothing more than a separate receiver with an arrangement for automatically changing the frequency of the transmitting system.

No repeater stations have been found necessary or

have been employed in this entire system, it having been so arranged that practically every channel is a more or less self-contained area. What business has to be carried out between one channel and the next is carried out by relaying, but experience has indicated that this is used to a very small extent.

Some of the zones, as is indicated, are quite close together. Since, in order to obtain all the channels, it was necessary to work on rather close frequency spacing (approximately 10 kilocycles) it is obvious that sharpness of tuning is one of the prerequisites for the successful operation of a system such as outlined. The development of selectivity filters previously referred to, solved this problem and has resulted in a situation where no interference is experienced between one channel and the next. In other words, the system as set up from that standpoint has shown itself to be entirely successful. A point that ought to be noted in this connection where such a wide flung system is involved is that natural attenuation makes it possible to operate two frequencies very close together in different portions of the system and yet have each one of them cover a channel of its own without any interference between them. For example, channel *A* covering the six stations in Michigan and Wisconsin operates at approximately 50 kilocycles without interfering in any way with channel *H* which operates around Philo at approximately 46 kilocycles; there is no other barrier except distance between the two channels in question, both being connected on the same 132-kv. system.

A unique use of a common frequency by two independent operating companies for inter-communication has been carried out in the territory around Shelby and Canton. Here a frequency of 90 kilocycles is used as a common frequency between the system of the Ohio Power Company and that of the Ohio Public Service Company. The Ohio Power Company's stations at Canton and Shelby are enabled to communicate with the Ohio Public Service Company's station at Massillon over the common inter-system channel between these three stations.

Cost of Installations

The cost of installations, of course, will not only vary with the type of sets employed but with the number and the voltage of the coupling points at a particular station and whether or not more than one frequency is employed at that station. Up to the present time line coupling exclusively has been employed on our 132-kv. system. It is possible, of course, to reduce this cost considerably by going to bus coupling. However, on the basis of the coupling practise followed, which has been fully described, the average cost per terminal has been running in the neighborhood of $15,000.00. This includes all the overheads. The cost of the 30 terminals therefore represents an investment of approximately $450,000.00.

These 30 points provide communication for a total of 1340 linear miles of 132-kv. line. It is estimated that the cost of a single leased line to provide approximately equivalent communication would amount in rentals to approximately $72,500.00 per annum.

Complete data on maintenance are not available over the system as a whole but on one portion of the system, where cost records were kept, the maintenance cost, including all the necessary personnel, of 18 sets in 1928, was approximately $9000.00 or $500.00 per year per set. Utilizing this unit figure, the maintenance for the 132-kv. system represents a total of $15,000.00 per annum. Allowing 15 per cent for fixed charges, the total cost of the carrier communication system is equal to $82,500.00 per year, the difference between the two forms thus being a total of $10,000.00 per year. Against this additional expense there is the following to be balanced:

1. Quality. The quality obtained over the carrier system has in general been equal to and in many cases better than what would pass for good commercial telephone quality. It is generally equal to the quality obtained in an all-cable commercial system, and in the territory covered, it is practically impossible to obtain an all-cable line of any appreciable length.

2. Reliability. The reliability of the carrier communication system has undoubtedly been superior to that of any other form of communication obtainable. This, however, will be discussed later.

Maintenance

The extent of the maintenance required has been discussed and some data with regard to maintenance have been given in the detailed analysis of the various phases of the equipment. In general, maintenance has been confined to routine inspection. Many matters that have given trouble considerably during a portion of the time covered have, through attention to that particular phase, been brought up to the point where they have been completely eliminated as a main source of trouble. Today, therefore, with the elimination of coupling, calling system, and similar troubles, only routine maintenance is necessary.

The cost, as already indicated, is not available for the entire system but the experience gathered on a portion of the system indicates that it runs $500.00 per terminal per year. It is believed, however, that no small portion of this is attributable to expenditure involved in training new personnel, etc., and that as time goes on, this figure can be cut from 20 to 30 per cent.

Reliability

The experience on our system has been that in many cases when contingencies develop that cause a breakdown of supporting structures or of lines that provide commercial communication, the carrier system of communication, depending upon the transmission line for the guidance of high-frequency current, was still operative.

Typical of the many cases experienced along this line are the following:

In June of 1929 important circuits of the private telephone system used for dispatching between the Stanton plant and the Pennsylvania Power & Light system went out during a storm and were out for a total of 19 hours and 48 minutes. The communication between Scranton (see Fig. 27) and other points of the Scranton electric system provided with private commercial telephone service was interrupted for periods ranging from three hours upwards. The carrier telephone system, however, functioned perfectly at Scranton during all this period.

On June 30, 1929, a severe thunderstorm in Indiana resulted in loss of all private telephone communication used for local dispatching between Marion and Muncie, (see Fig. 4). During that period, however, as well as during other periods under similar conditions, continual communication by means of carrier was maintained between these two points and was the only form of communication.

Again, on May 2, 1929, a very severe sleet storm was experienced in the South Bend territory. A leased commercial circuit, the majority of which is in cable, was used in this territory for local dispatching between seven points on the local system. The phones on this leased circuit went out of service and remained out for periods from 44 to 73 hours. During this entire time carrier communication was maintained continuously between South Bend, Twin Branch, Fort Wayne, Marion, Muncie, Lima, and Fostoria, excepting for a period of approximately 11 hours when carrier communication was not available between South Bend and Twin Branch while the lines between these two points were taken out of service and grounded for making repairs. During this storm, conductors of both circuits between South Bend and Twin Branch were broken and on the ground but regardless of this condition carrier communication was actually maintained between South Bend and all other stations on the channel until the circuits were actually grounded at both ends for making repairs.

From a reliability standpoint we believe, therefore, that carrier, properly applied, installed, and maintained, provides over our system a continuity of service economically possible by no other means of communication.

Traffic

Table III gives the results of a traffic check made on a channel with 11 sets. Turner and Switchback were the main dispatching points on this channel. From the data shown the following are obtained:

(a) Total number of two-way conversations, 1016.

(b) Average number of times channel was used per hour, 14.1.

(c) Average duration of a conversation, 1 min., 39 sec.

(d) Percentage of time channel was in use, 38.5 per cent.

TABLE III
SHOWING RESULTS OF TRAFFIC COUNT OVER A SINGLE CHANNEL OF 11 STATIONS. COUNT TAKEN OVER 9 WEEK DAYS DURING HOURS 8 TO 12 A. M. AND 1 TO 5 P. M.

Stations	Total calls placed or received	Average times used per day	Total time in use during 72 hours		Average percentage of time in use
			Hours	Min.	
Philo	58	6.5	1	39	2.3
South Point	123	13.6	2	53	4.0
Turner	556	61.8	15	14	21.0
Logan	201	22.3	5	20	7.4
Sprigg	91	10.1	2	46	3.8
Switchback	459	51.0	12	38	17.5
Saltville	24	2.7	0	36	.8
Kingsport	81	9.0	2	4	2.7
Glen Lyn	79	8.8	2	4	2.7
Roanoke	216	24.0	6	49	9.5
Lynchburg	144	16.0	3	46	5.2
Totals	2032	226.0	55	49	76.9

The transmission of meter readings and similar routine dispatching data from the controlled stations to the dispatching points can usually be done at off-peak periods. Scheduling of the use of the channel by the stations on it and the transmitting of record data at off-peak periods have been of great help in making one channel serve a large number of stations. The party line feature permits routine communication to proceed and enables any operator to break in whenever it is necessary to use the channel for more urgent matters. One advantage of a large channel as indicated in this territory is that the chief system operator may communicate directly with all plants and important stations under his control. Regular communication is carried on between Turner station (ref. KL-49) and all other stations on the *K* and *L* channels. When the traffic figures shown were obtained, Philo (ref. HK-32) and South Point (ref. K-46) were included in this channel. By systematic scheduling it is believed that double the traffic shown here can be conveniently handled over a single channel.

Safety

Nine failures of coupling capacitors have occurred so far and in all these cases the protective system used between the power conductors and the equipment and operators has functioned correctly and no damage or injury of any kind has occurred to equipment or operators. With the placing of all lead-in conductors underground the present extremely small hazard will be further reduced. The hazard is surely less than that existing in connection with the use of telephone circuits strung on transmission lines or even of some commercial overhead circuits. The experience at Canton when the power conductors came in contact with the antenna coupling wires resulted in damage to equipment only. In all our carrier experience no case has ever occurred where injury to any person has resulted from failure of the equipment.

Portable Sets

It is believed that the data cited indicate that the development and application of carrier to the higher voltage lines has now reached a high level.

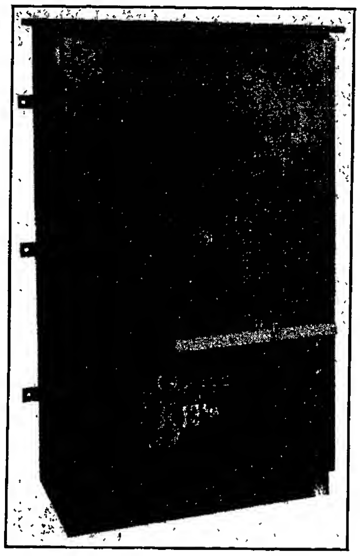


Fig. 34—General Electric Co. Type KCA-200 Booth Type Set

Very little has so far been done, however, toward applying carrier to the communication requirements of transmission networks operating with voltages of the order of 44, 33, and 22 kv. Here an entirely different problem is met. The lines are not built as strongly; more tap lines, transformers, loop circuits, sectionalizing points, etc., are encountered than on the higher voltage lines, all of which tend to increase attenuation and make the system unstable. Also the points at which communication is required are much more numerous and many of the points are located in out of the way places difficult to get to for inspection and maintenance. Dependable power supplies such as station storage batteries are not available.

Fig. 34 is an illustration of a booth type set designated type KCA-200 recently developed by the General Electric Company for this work. It is built for either indoor or outdoor mounting and may be used with either dry cell batteries for intermittent service or with storage batteries for continuous use. It operates on the simplex, single-frequency, interphase principle, and is provided with selective signaling. A loud speaker may be connected for voice calling.

Fig. 35 is a group of diagrams showing schematically the circuits for transmitting and receiving. Two tubes are used, operating as oscillator and modulator respectively for transmitting and detector and audio amplifier for receiving. The set has an output of 0.25 watt.

Fig. 36 is a photograph of a portable type set, designated type CC-5B, made by the General Electric Company. It uses one dry cell tube for both oscillator or detector, operating on the simplex, single-frequency principle, either interphase or phase-ground return.

Fig. 37 is a group of diagrams showing schematically the circuits for transmitting and receiving.

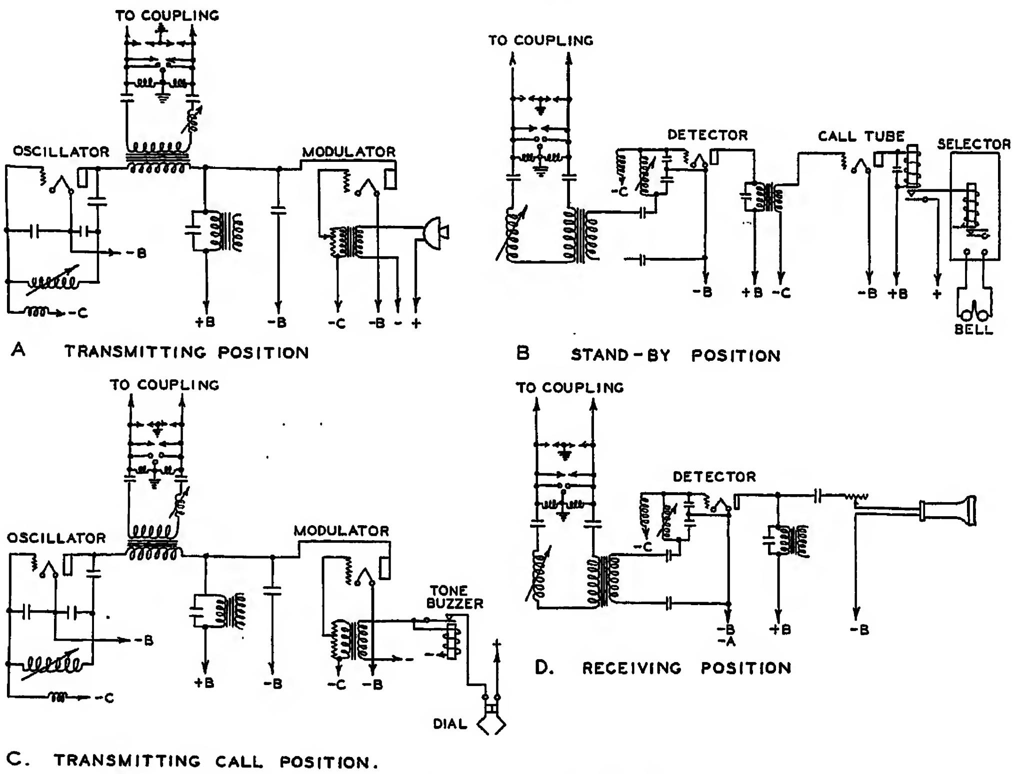


Fig. 35—Schematic Circuit Diagrams of Booth Type Set

Fig. 38 shows schematically the installation of one of these sets at a sectionalizing point for patrol communication. Here the set is used with phase-ground return circuit.

At present a trial installation is being made on a 50-mile, 33-kv. line from Ashland to Haldeman, Ky. of three type KCA-200 sets and two type CC-5B sets

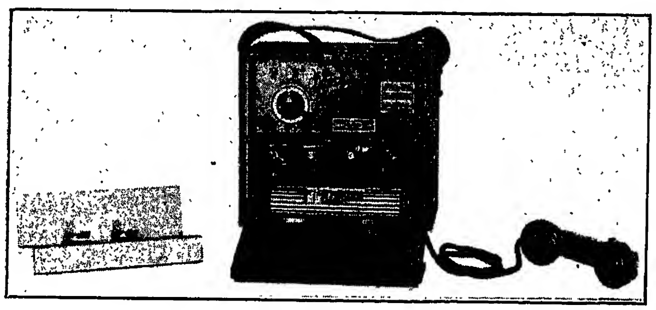


Fig. 36—General Electric Co. Type CC-5-B Portable Type Set

located at sectionalizing points and communicating with a type KCA-100 terminal set at Ashland.

Fig. 39 shows a typical pole type installation adopted for either type of set.

Another experimental installation is being made on a portion of a 44-kv. transmission network of approximately 300 line miles located around Cabin Creek,

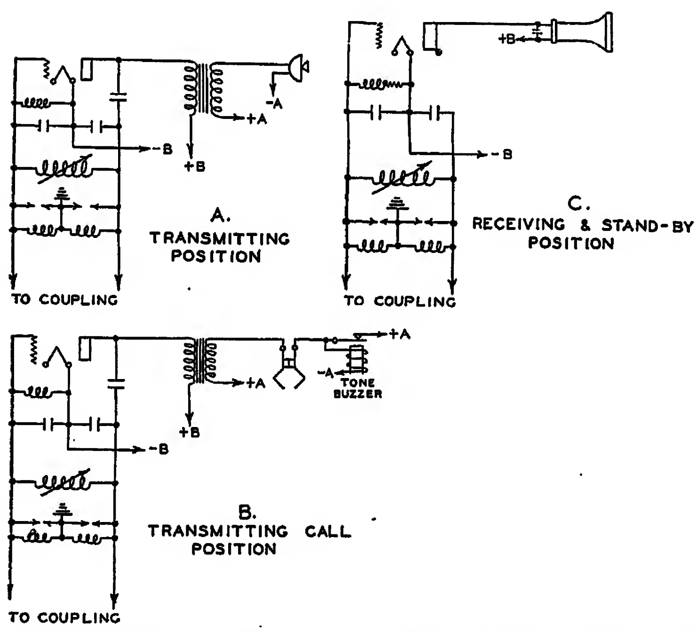


Fig. 37—Schematic Circuit Diagrams of Portable Type Set

West Virginia. This system covers very mountainous country. The dispatching and patrol communication has heretofore been done over leased commercial circuits practically all of which are open wire lines. Experience with the commercial circuits in this particular territory has not been fully satisfactory and it is planned, therefore, to introduce carrier as a means of communication. Ten type KCA-200 sets are being installed initially. It is planned that these two experi-

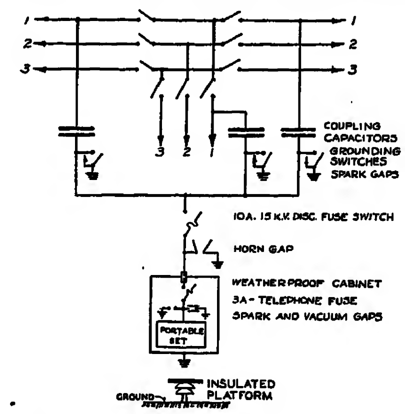


Fig. 38—Schematic Diagram Showing Phase, Ground Return Coupling, and a Portable Set

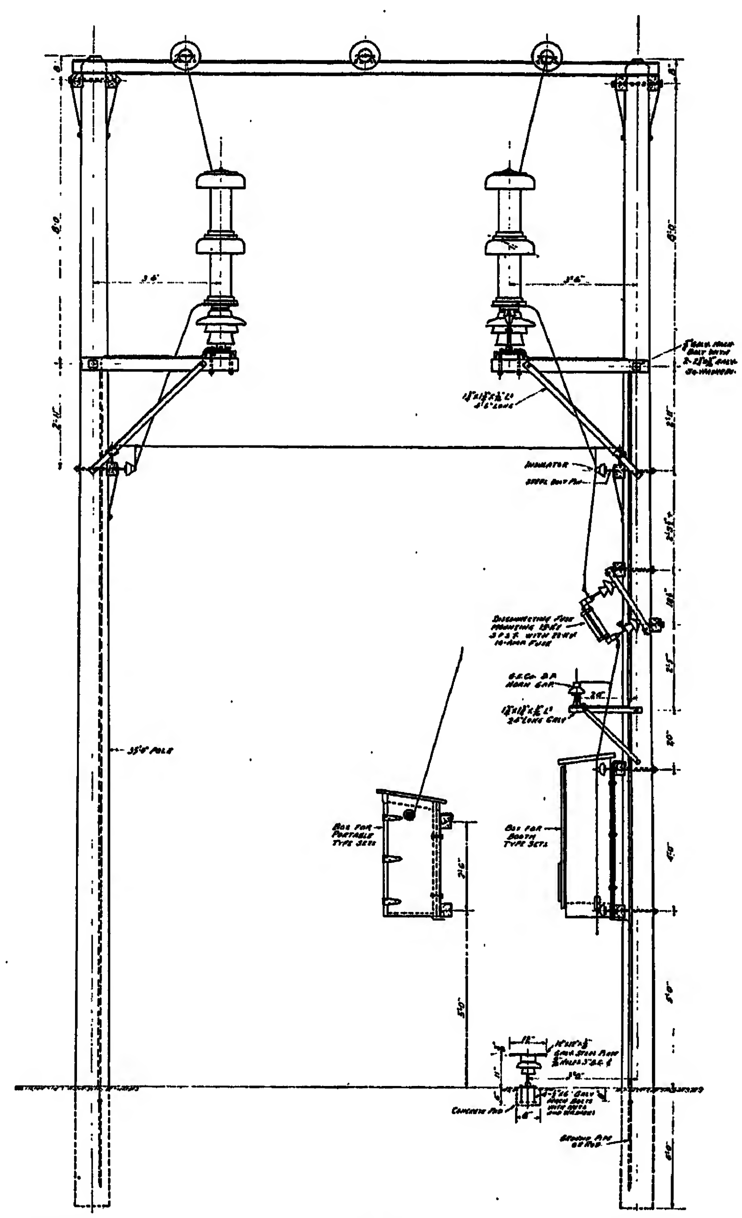


Fig. 39—Outdoor Installation for Booth and Portable Sets

mental installations of small sets on low-voltage transmission networks will provide the experience for the development of carrier systems suitable for providing reliable, and economically justifiable communication over such lines for dispatching and patrolling communication. It is also planned to do work towards applying carrier for communication between patrol points along the 132-kv. lines and the terminal stations at each end of the lines. Only low-power sets are required and the problem therefore reduces itself mainly to developing adequate and inexpensive coupling equipment.

After more actual experience has been secured with carrier on low-voltage systems it is hoped that it will be possible to present this phase of carrier-current development before the Institute.

Future Line of Development

The experience obtained with the carrier system of communication described, it is believed definitely shows the vast amount of development work that has been done in the last decade in connection with carrier. Today, while it can be definitely stated that carrier has proved its indispensability as a tool in the operation of transmission systems, there are nevertheless certain phases of development that ought still to be carried further if its usefulness is not to be restricted and its use hampered in the future. Among those definitely indicated are the following:

1. It is believed that too large a percentage of the cost of an installation is at the present time still taken up by the coupling system. That the use of coupling capacitors will be continued in the future, there is every reason to believe at the present time, but it is not equally certain that the present form is the ultimate form. Capacitors employing perhaps different design principles in order to allow an appreciable reduction in cost are needed.

2. Teletyping. A large portion of the communication of a transmission system of the type described can be handled by means of printing typewriters giving a permanent record, utilizing the same coupling equipment and perhaps the same transmitting and receiving equipment. In many cases this ought to make possible a wider and more effective use of a given channel.

3. Used on lower voltage circuits and portable use. Very little work has been done on the development of carrier for moderate voltage circuits such as 44,000 volts and below, and particularly has very little work been done on the development of sets of moderate cost for this service. Included among these are portables and equipments of the same type. A very definite field is open here that would again offer communication on lower voltage lines of higher reliability than is obtainable at the present time and certainly at no greater cost.

4. Further work should be done in the direction of providing additional channels that will undoubtedly be needed in the future as systems expand. It is obvious that little more can be done in the direction of reducing the number of frequencies employed in a given channel so that the logical direction of development would be in the path of reducing the width of frequency band required per channel. It is possible that the development of the single-sideband carrier system will answer this purpose but the objection to it in its present form is its greater cost. A development that would obtain substantially the same results at much lower cost is very definitely needed.

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Discussion

R. J. Wensley: Mr. Sporn makes a statement that there is no paper by a large system operator covering the system they have in use. He also omits mention of a paper presented by Woodcock and Robinson[1] of the Alabama Power Company at the Atlanta meeting in October, 1928, in which they described the large double-frequency carrier system now in operation on the Alabama Power Company System. It describes the satisfactory results obtained with high-power double-frequency carrier telephone communication over a system of 2000 mi. of 110-kv. transmission lines. On that system there are four operating channels with a lower frequency of 27 kilocycles. They are having no interference trouble according to latest reports.

The Indiana Electric Corporation has over 20 sets of the high-power two-frequency in operation on a much more compact but very intricate network over the state of Indiana. That company is quite satisfied with double-frequency operation and finds no bar to successful load dispatching.

We hold no particular brief for the double-frequency system. It would be quite as easy for us to build the single-frequency. It only means adding a few more vacuum tubes to the tuned circuits.

We are wondering as to the actual future of carrier equipment. Our own feeling is that wherever fully protected sheathed cable on high-grade pole construction is available, leased wires through those cables probably offer the best means of system communication. But as soon as you get out into the areas where cable is not available, the stronger construction of the transmission system offers a more dependable means of communication than the much lighter built telephone long-distance circuits with the small wire and the light construction.

One point in answer to Mr. Sporn's requirement of a cheap means of coupling, we have developed a form of coupling capacitor which looks like a string of suspension insulators and requires no other construction than to hang the string on the tower.

J. D. Burbank: We have a system of about ten or twelve stations on our lines, and most of it is General Electric equipment. We find that it gives us very satisfactory communication, but there are certain points concerning which I should like to ask Mr. Sporn to give his experience.

We find that the control system used on single frequency on the voice circuits tends to impair the quality, while if you go to the double frequency system, you run into complications due to the fact that the transmission characteristics are not the same over different frequencies. It is rather difficult to find two bands which will be sufficiently wide to carry sidebands as well as your carrier waves for those two frequencies. That is the difficulty we are up against.

I was just wondering whether he had any trouble with the quality, in using a single-frequency system, due to the blocking action of his control tube.

Furthermore, we find the selective ringing system is by no means always perfect, and I should like to know just what his experience has been.

In general, I would say it is very satisfactory. We have had a number of heavy sleet storms, and that has been the only communication available as a rule. The private lines are wiped out, and the open-wire Bell lines are not much better.

As regards the coupling arrangement, we use all the systems that he mentioned. We use the mica type and the cable type. We have one of the original oil capacitors, as a matter of fact the first one ever installed, at Niagara Falls. The oil capacitor is very satisfactory. We have had no trouble with it. We also have some of the Ohio Brass Company porcelain type which have been satisfactory to date. Those are newer. We found, however, that in a good many cases the old coupling wire comes in very handy, and it is far less expensive than the other types. You can do by-passing, etc., much easier with it.

Alexander Nyman: (by letter) It would be interesting to know what the experience has been with regard to the surge protection introduced on account of the capacity connected between the transmission line and ground. As is well known, the surges and particularly, lightning surges, have an extremely steep wave front, and it would be reasonable to expect, therefore, that a capacitor would absorb a considerable amount of the energy of this steep wave front, thus reducing the shock on the other apparatus and in a way, acting as a lightning arrester. If such an installation has been present for any length of time, the operators near this particular installation, should certainly be aware of the reduction of surge troubles at their stations, and it also seems possible that some of the break-downs on the capacitors are really due to lightning surges, the condenser thus serving as a protector for the remaining apparatus and sustaining the damages which could have otherwise inflicted much more serious losses on other apparatus of the system. It is interesting to note that in the actual installation of the first mica condenser at Canton and Philo in 1925, these condensers have stood up continuously since that time without any trouble.

With regard to carrying out impulse tests, especially on apparatus which would be later put into actual service, this is a very dangerous procedure, since a condenser subjected to the necessarily high strain of such impulse test, is likely to have incipient damages, not necessarily in the dielectric producing the capacity but in impregnating materials or mounting parts such as bakelite rods or porcelain separators. A condenser weakened by

1. *Carrier-Current and Supervisory Control on Alabama Power Company System*, A. I. E. E. Quarterly TRANS., Vol. 48, Jan. 1929, p. 214.

such test and later placed into service, would therefore be more likely to break down due to a subsequent surge.

During recent years, considerable development work in new types of condensers has been carried out with the result that a type of coupling condenser has been developed which is considereably cheaper than the present type of mica, cable, or porcelain condensers, which has a higher impulse ratio of the order of 10 to 12, and which permits placing a much larger capacity within the same space than the present type of condensers.

Philip Sporn: In answer to Mr. Wensley, I am sorry if we overlooked the paper of Messrs. Robinson and Woodcock. The article mentioned as item No. 35 in the Bibliography is, I think, on the same system; it is indicated as the Southeastern Power & Light Company. There is a reference, therefore, to that system although not to the particular paper.

I believe there is no real difference between Mr. Wensley and us on the question as to whether a two-frequency system will or will not work all right. We set down as one of the fundamentals, ability to furnish a maximum number of channels on any one system. The idea that we started out with is that it is possible to have a large power system and a four-frequency carrier system that will work all right, but the question is: What will happen when the two channels that four frequencies will give aren't enough?

Our stand in the matter—and we believe we have tested the curve a little further to the breakdown point than it has been tested in Alabama, perhaps—is that the two-frequency system will work, but obviously as long as you have to have two frequencies there will come a time when you will be able to have only half the channels that a single-frequency system will give you. If you don't need so many channels, the two-frequency will be all right. If you have to have all the channels you can get, obviously you are wasting possible channels. We have reached the point on our system where we can't waste any channels. We must have all we can get. That is the point I made.

There is also the question as to whether it is a fundamental requirement to have all the people on a given channel come in at any time during the conversation. There is much difference of opinion on that. Our own operating people requested that we develop this. They couldn't operate safely unless everybody who had any business on the channel was able to come in on an emergency regardless of other conversations on his channel. We had two very bad spills as a result of not being able to do that with another carrier system that we described. If the electrical system is set up so that the load dispatcher is czar of the system and nobody else dare say anything, I imagine the other set is all right. Our own people don't work that way.

As regards the field of application for carrier and cable, here, again, I think we are in entire agreement. Where the distances are short, and that is a point Mr. Wensley didn't mention, and where you have available cable service, I think you cannot justify carrier. That does not happen to be the case on most high-tension overhead systems. There are many sections where there is no reliable telephone service available.

Mr. Burbank brought up two or three questions, the first about quality. On the sets we have been able to get in the last two or three years the quality is comparable to very good Bell service, and better than a lot of Bell.

The question of selective ringing that Mr. Burbank mentions was one of the weak things in the system, and we think today probably is still open to improvement. We supplement the selective ringing by loud-speaker calling and find it very satisfactory.

As regards the question raised by Mr. Nyman, there is no doubt that some of the failures of mica capacitors mentioned were due to lightning; that is exactly the point we made, that the mica capacitor is fundamentally unsuited to stand impulses as well as capacitors utilizing other material, as for example, oil-impregnated paper. It happened that the Canton capacitors stood up well but other capacitors of the same type which went into service much later failed after a very short time in service. Of course none of the capacitors which were used in the laboratory were actually put into service later. As Mr. Nyman points out, it would be entirely unfair to the apparatus and besides would be a rather risky operation. The new capacitors which Mr. Nyman mentions as having an impulse ratio of 10 to 12, are unusually interesting, particularly if they actually meet the claim made for them. It will be interesting to find out for what type of impulse wave the impulse ratio of 10 to 12 is predicted.

Automatic Regulation of Synchronous Condensers
Equipped with Superspeed Excitation

BY L. W. THOMPSON[1] and P. J. WALTON[2]
Non-member Member, A. I. E. E.

Synopsis.—This paper describes extensive field tests made on the super-high-speed excitation equipment used with the 30,000-kv-a. synchronous condensers at the Plymouth Meeting Substation of the Philadelphia Electric Company. Oscillograms and calculated curves showing the performance of the synchronous condensers with this equipment are included, together with a discussion of the results obtained.

* * * * *

THE speed and maximum voltage characteristic of the excitation system used on synchronous condensers is of prime importance in determining the amount of corrective kv-a. which can be furnished by the condenser during a system disturbance.

On the Conowingo Line at the Plymouth Meeting Substation there are installed three 30,000-kv-a. condensers equipped with a supersystem of high-speed excitation and a method of control that is sufficiently novel to warrant a general description.

To obtain the same corrective kv-a. with ordinary types of excitation, a much larger installation of condenser capacity would be required.

These machines are installed for the purpose of voltage regulation of the system and as an aid during transient conditions. Since other articles have described the synchronous condensers, no description is given herein.

Excitation for the main exciter field is furnished from a subexciter. The subexciter itself is of standard design and is a straight shunt-wound machine. The main exciter is of very special design. It has laminated poles and yoke, heavy series winding (which will be referred to later), and an armature ceiling voltage of approximately 1000. Also, it is provided with two shunt-field windings.

The main shunt field is directly connected to the subexciter through a simple motor-operated rheostat which if properly set will give in general the proper main exciter volts to produce the desired kv-a. on the condenser under steady conditions of load and voltage.

At this time there will be little or no current in the second or regulating shunt field on which the regulator contacts operate. This of course is very desirable.

This regulating or auxiliary field itself will not produce an exceedingly high rate of rise of the exciter voltage, but can take care of ordinary conditions of load and voltage that may come during normal operation. This range of the auxiliary field itself is somewhat unusual as it is capable of controlling the condenser from approximately 20,000-kv-a. lag to 60,000-kv-a. lead under all steady-state conditions, and if there were any requirement for it even this range could be extended.

The regulator is of the high-speed type equipped with a three-phase torque motor as the master voltage element, so as to provide proper response of the regulator on any type of disturbance. The relay contacts of this regulator are connected to the auxiliary field through an unbalanced resistance bridge so that a reversal of the auxiliary field can be obtained, depending on the ratio of time opened to time closed of these relay contacts. This regulator controls the line voltage under normal conditions because of its ability to vary the condenser kv-a. through the above mentioned range.

However, for transient conditions, resulting from line-to-ground, double-line-to-ground, or three-phase faults when the average line voltage is depressed five per cent or more, the main shunt field is brought into play by means of a second master voltage relay which operates a high-speed contactor, opening the regulating field and cutting out the resistance in series with the main shunt-field winding. When this resistance is cut out of the main field, a rate of rise of approximately 7000 volts per sec. is obtained on the main exciter. This resistance is not cut-in again until the line voltage is restored or until the kv-a. per condenser has reached approximately 60,000.

At this time a current relay in the main condenser field operates at a value corresponding to this maximum kv-a., which again inserts the resistance in the main exciter field, the auxiliary field being closed simultaneously with the insertion of this resistance. This transition between the two shunt fields is very smooth and does not produce fluctuations to any extent in the main exciter voltage, or any fluctuations in the kv-a. on the main unit, as the transformer action between these fields tends to keep the flux constant. As the main field tends to collapse, it induces substantially a corresponding increase in ampere-turns in the auxiliary field sufficient to maintain the original flux produced by the main field. After this change the regulator again operates upon the auxiliary field either to maintain voltage or a maximum kv-a.

At a time when conditions return to normal, the regulator rapidly backs the exciter voltage down from its original high value to the value required to give the proper voltage on the system bus. This rapidity of de-

1. General Electric Co., Schenectady, N. Y.
2. General Electric Co., Philadelphia, Pa.

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down is due to the auxiliary shunt field at this time receiving a reversed voltage, which in turn accelerates the decay of the main exciter. This scheme of connections is shown in Fig. 1.

Discussion of Curves and Calculations

The benefit derived from superexcitation in regard to increased condenser capacity can best be understood by considering a specific example.

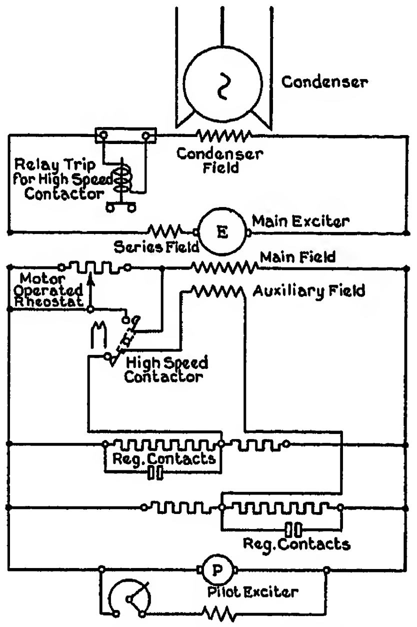

Fig. 1—High-Speed Excitation Scheme for Synchronous Condenser

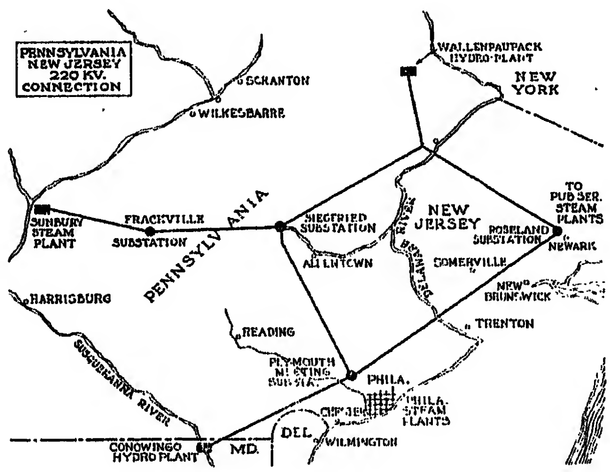

Fig. 2—Map of Interconnection

The diagram of system connections is shown in Fig. 2; schematic diagram of system in Fig. 3.

Consider Siegfried, Conowingo, and Westmoreland interconnected, Siegfried floating on the line, and Conowingo feeding 150,000 kv-a. to Westmoreland. If a two-conductor-to-ground fault occurs at *F* on the Siegfried bus and two condensers are operating at Plymouth Meeting at 10,000 kv-a. leading, giving a total of 20,000 kv-a., there will be an instantaneous rise to 43,000 leading kv-a. from the Plymouth Meeting condensers at the moment of fault.

After the fault has been applied, the condenser kv-a. will continue to rise as determined by the superexcitation system from the above-mentioned initial value of 43,000 kv-a. to approximately 150,000 kv-a. in 0.5 sec. This is shown graphically in Fig. 4.

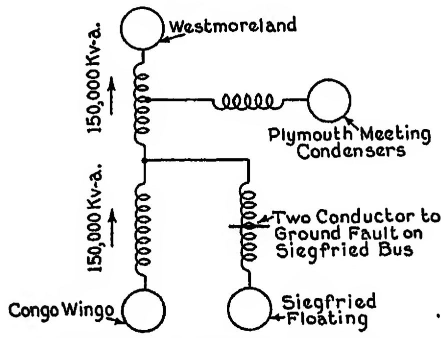

Fig. 3—Schematic Diagram of System upon Which Calculations Were Based

The fault *F* on Siegfried bus results in a decrease in positive phase sequence voltage at the terminals of the condensers of 30 per cent and an increase in positive phase sequence condenser current of 208 per cent.

Conowingo assumed to be furnishing 150,000 kv-a. to Westmoreland

From Fig. 5 it is seen that two condensers with standard excitation are, at the first instant, equal in corrective effect to two condensers with superexcitation, but at the end of one-half second, approximately ten condensers with standard excitation are required to give corrective effect equivalent to two condensers with superexcitation.

Before the fault occurs it is assumed that the condenser bus voltage is being held at its proper value by the 20,000 kv-a. delivered by the two connected condensers. In order to deliver this same initial kv-a. with a larger number of condensers with ordinary excitation, the excitation on each condenser would necessarily be less than that of either one of the two units with superexcitation.

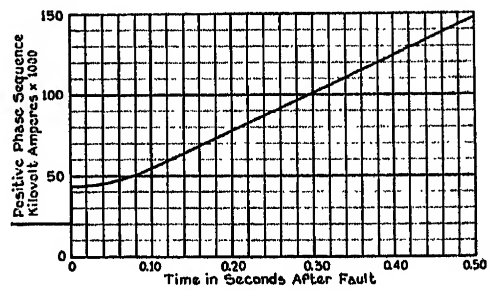

Fig. 4—Graph Showing Rise of Condenser Kv-a. after Two-Conductor-to-Ground Fault

Referring to Fig. 5, the integrated kv-a. or kv-a. seconds shown, could be furnished by approximately five and one-half condensers with standard excitation at the end of 0.5 sec., but the maximum instantaneous

kv-a. at the end of 0.5 sec. with two condensers having superexcitation is approximately equal to ten condensers with ordinary excitation.

Requirements

It was required of the condenser that it be capable of operating at 10,700 kv-a. lag up to 55,000-kv-a. lead;

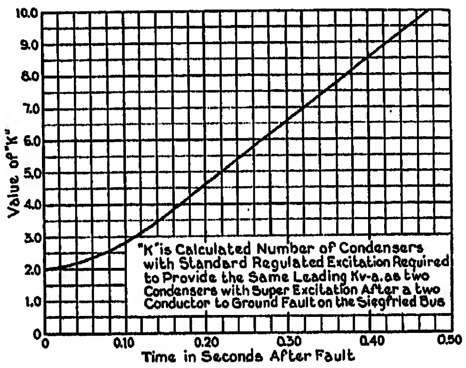

Fig. 5—Curve Showing Number of Condensers Needed with Standard Excitation to Give Same Correction as Two Condensers with Superexcitation

also with the condenser carrying 10,000 kv-a. lead initially, the time from the occurrence of a fault on the system to reaching 55,000-kv-a. lead to be not more than 30½ cycles on the basis of 60-cycle time, the exciter voltage to be not more than 900-volts ceiling.

These requirements meant that the voltage regulator must operate over a range of from about zero volts to 900 volts.

This condition will be appreciated when it is remembered that the usual voltage regulator is required to operate over a range of from 70 to 140 volts or a range of 1 to 2.

In case of a short circuit on a line, it is possible for the voltage of one-phase to be higher than before the short circuit occurred and for this reason, the voltage-regulator element and the element for applying the superexcitation each consists of a three-phase torque motor.

To insure the high-speed feature being applied independently of the regulating equipment used for normal conditions, and to have it come in with the least amount of time delay after the occurrence of a fault and to adjust the voltage at which it would be applied independently of other conditions, a separate torque motor was used for the purpose of applying the high-speed excitation in addition to the torque motor operating as a normal voltage regulator.

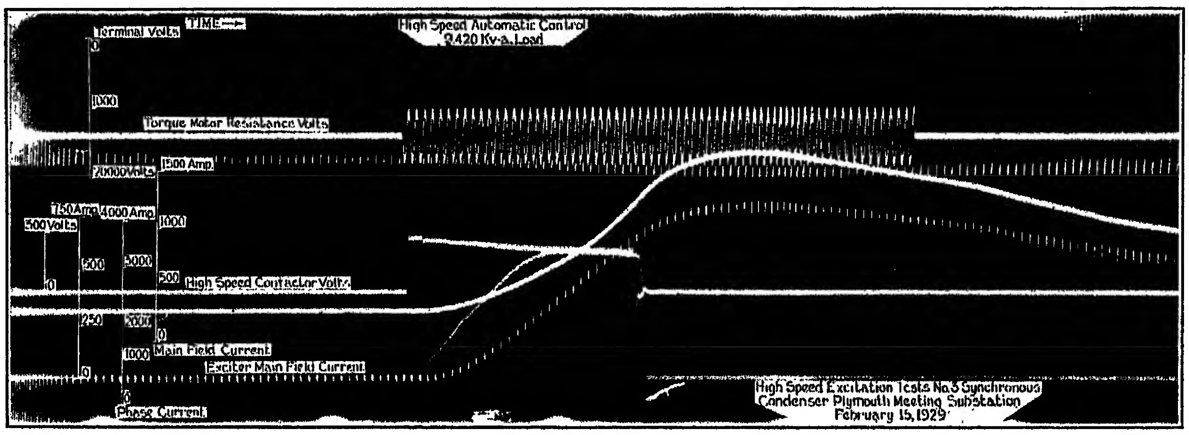

Fig. 6—Oscillograph Records of High-Speed Excitation Tests

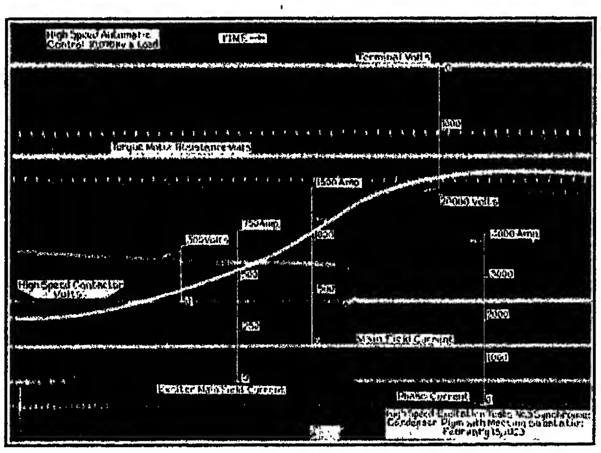

Fig. 7—Oscillograms of Test on Condenser Having High-Speed Excitation

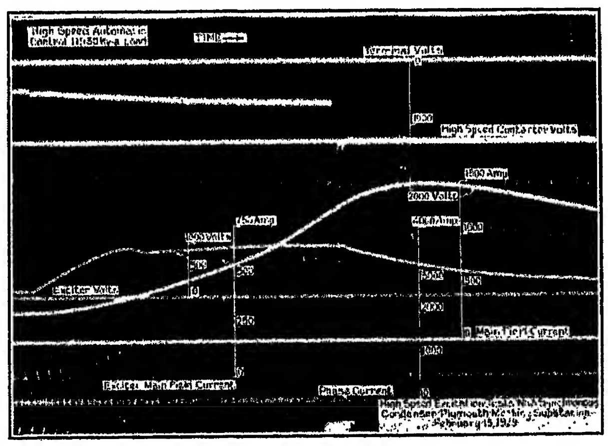

Fig. 8—Oscillograms of High-Speed Excitation Test

Tests

The kv-a. taken by a condenser for a given field current depends upon the voltage at the condenser terminals. It was impossible to hold constant voltage when suddenly increasing from 10,000 kv-a. to 55,000 kv-a. owing to the reactance of the transformer bank, to the tertiary winding of which the condenser is connected.

In testing, therefore, to determine the time to increase from 10,000 kv-a. to 55,000 kv-a., the starting point was taken as the field current to produce 10,000 kv-a. at rated voltage 13,800 volts; and at the starting point, the voltage was reduced by having lagging kv-a. on another condenser to try to reach 13,800 volts when the kv-a. reached 55,000 on the condenser under test.

In other words, the time is that required to build up the field current of the condenser, as the a-c. amperes depend on the condenser field flux, and tests showed that there was practically no time delay between field amperes and a-c. amperes and consequently field flux.

Referring to Fig. 6, the torque motor resistance is the voltage across a resistance inserted in the torque motor circuit to reduce the voltage applied to the torque motor to correspond to a short circuit on the system.

When the system voltage dropped as indicated by the voltage across this resistance, it will be noted that within a cycle, the torque motor contact closed, applying voltage to the coil of the high-speed contactor.

The instant when the high-speed contactor closed is indicated by the point when the exciter main field current starts to increase.

Following the short-circuiting of the resistance in the exciter main field by the high-speed contactor, the field current of the main exciter rapidly increases, building up the exciter voltage to the desired value, approximately 900 volts, as shown in Fig. 7. After this the exciter voltage held practically constant because of the combined effect of lowering the pilot exciter voltage by omitting its series field and by the action of the series field of the main exciter. This is also shown in Fig. 8.

With the adjustments used, the kv-a. of the condenser built up to about 73,000, or well beyond the 55,000 kv-a. agreed upon.

Summarizing these tests, the time required to reach the required kv-a. is approximately 25 cycles on a 60-cycle basis, though in actual practise the required kv-a. would be reached much earlier because of an instantaneous increase of kv-a. through a reduction in terminal voltage resulting from a short circuit on the line, to which is added the subsequent increase due to the high-speed excitation. Additional benefit in regard to rate of rise is obtained from a very heavy series field on the main exciter which tends to raise the exciter voltage due to the transient increase in the condenser field current, raising the exciter voltage before any of the automatic equipment installed for this purpose comes into play.

Discussion

J. H. Ashbaugh: It is unfortunate that the author did not show a diagram of the regulator itself, but we assume it is of the vibrating type. This being the case, the current in the auxiliary field which is handled on the vibrating regulator contacts must vary over quite a range in order to take the main machine from 20,000 kv-a. to 60,000 kv-a. lead. Probably a follow-up arrangement has been provided on the motor-operated rheostat in order to keep the current at a small value in the auxiliary field.

We have been using an arrangement somewhat similar to this in paper mills and steel mills, and have found it to be quite satisfactory. In some cases we used a booster in place of the auxiliary field, and then a wheatstone bridge on the field of the booster. These have been worked out for both the vibrating and the carbon-pile type of regulators. We have also used this wheatstone bridge arrangement with the exciter rheostatic regulator, working directly on the main field of the main exciter.

The authors state that this regulator operates over quite a wide range in voltage from 0 to 900, whereas the usual voltage regulator is limited in a range of from 70 to 140 volts or 1 to 2. I don't feel they mean quite this, as we have had broad-range regulators on the market for years in which the range was limited only by the exciter itself and not by the regulator. These unlimited range regulators are available in both vibrating and exciter rheostatic type, in fact, any regulator which does not obtain its power from the exciter is not limited in range over which it must work.

P. J. Walton: Replying to the discussion by Mr. Ashbaugh, the regulator is of the vibrating type, as indicated by the regulator contacts in Fig. 1 of the paper. As to the range in the current in the auxiliary field, it so happens that the fixed excitation in the main field plus positive excitation in the auxiliary field is sufficient for 60,000 kv-a. lead, whereas the fixed excitation in the main field less negative excitation in the auxiliary field of the same value is sufficient for 20,000 kv-a. lag. There is no follow-up on the motor-operated rheostat.

As to the wide range in voltage, the main exciter actually operates over a range from a negative voltage instead of zero voltage, and after super-speed excitation has been applied, the control is taken over by the regulator at a time when the exciter voltage is 900 volts, although this voltage is rapidly decreased after the voltage regulator takes control.

Polyphase Induction Motors
A Labor Saving Method of Calculating Performance from Previously Determined Constants

BY W. J. BRANSON[1]

Associate, A. I. E. E.

***Synopsis.**—This paper presents a method of calculating polyphase induction motor performance which eliminates a large amount of detail work without making use of approximations which sacrifice accuracy. In any rigorous system for calculating induction motor performance, the determination of the relation between input and current values makes the greater part of the work.*

By the procedure here presented, the relation of watts to amperes for all cases likely to be encountered in ordinary design work may be accurately calculated once for all and recorded in a set of curves. When making practical calculations tedious detail work may be eliminated by taking the necessary values from the curves, in much the same way that sines are taken from sine tables.

The calculation begins with the torque, from which the corresponding secondary input is obtained by a simple formula. Then, by reference to the appropriate curves and a few simple slide rule operations, the primary and secondary currents are determined. With the secondary input and the current values known, the completion of the calculation requires nothing more than a few operations of simple arithmetic. The entire process for one load point may be completed in from five to seven minutes.

I. Introduction

THE methods most frequently used in calculating the performance of polyphase induction motors are:

(1) The Steinmetz analytical equations based on the "exact equivalent circuit."

(2) The various forms of the circle diagram.

With the exception of a slightly unscientific treatment of core losses, the Steinmetz equations are rigorously correct mathematical processes, but they require a large amount of detail work. Using ordinary facilities, the time required to calculate the output, revolutions per minute, efficiency, power factor, etc., for a single load point is usually about 40 or 45 minutes.

If properly constructed, the circle diagram also constitutes a rigorous mathematical process, but the forms commonly used and presented in text books are based on approximations which sacrifice accuracy while still requiring a very objectionable amount of labor.

II. General Character of the Process

This paper presents a method of procedure by which it is possible to complete an accurate performance calculation in from 5 to 7 minutes,—that is, in about one-sixth of the time required by the Steinmetz equations. The processes which eliminate so much detail work are somewhat analogous to the use of tables of trigonometric functions. If trigonometric tables did not exist, the easiest way to obtain the sine of an angle would be to construct an appropriate triangle and divide the side opposite the angle by the hypotenuse. Anyone who had occasion to do this frequently, however, would naturally discover that by constructing, once for all, a series of triangles, he could draw a curve from which the sine of any angle might be read directly.

In a similar manner, it is possible to make curves showing any desired geometrical relations of the circle diagram, corresponding to all possible combinations of motor constants; and, with properly constructed curves of this character available, a performance calculation for an ordinary polyphase motor requires no detail work beyond reading the necessary values from the curves and carrying out a few simple arithmetical operations.

III. Mathematical Basis Compared with That of the Steinmetz Equations

Although the mathematical processes used in preparing these curves are based on the circle diagram, they are exactly equivalent to the Steinmetz analytical

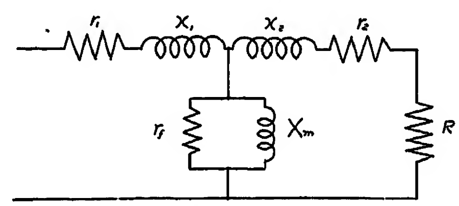

Fig. 1—The "Exact Equivalent Circuit"

equations except in one point, the treatment of core losses.

In the "exact equivalent" diagram (Fig. 1) the core loss is represented by a copper loss in a fictitious resistance unit, r_f. The location of this resistance in parallel with the exciting reactance, X_m, makes the core loss vary with the flux which crosses the air gap and consequently fall off as the load increases. For the ordinary transformer, this arrangement is probably as accurate as any that could be suggested. In the case of the induction motor, however, conditions are somewhat different. As the load increases, the core loss falls off slightly in the stator but at the same time increases in the rotor. Alexander Heyland suggested more than thirty years ago that the increase of rotor core loss

1. Designing Engineer, Robbins & Myers Inc., Springfield, Ohio.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

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should be assumed to be equal to and to offset the decrease in stator core loss, making the total constant at all loads; and this assumption, which underlies all forms of the circle diagram, has been approved explicitly or tacitly by nearly all writers on the induction motor.

This rather small difference in the treatment of core loss has been explained at some length because it introduces the only *discrepancy in results* between the system presented in this paper and the Steinmetz system which is given in text books and extensively used in practical work.

IV. Comparative Calculations

If the core loss be made equal to zero, that is, eliminated, the two systems will give absolutely identical results provided all the arithmetical work is correct. This is illustrated by the parallel columns below in which arithmetical errors have been avoided by the use of a calculating machine.

CALCULATIONS

From Equivalent Constants

By the Process Presented in this Paper	By the Steinmetz System
Data	Data
E = 1000	E = 1000
X_{sc}' = 10	x_1 = 4.09526
X_o' = 100	x_2 = 6.29199
Kp = 0.959047	X_m = 95.9047
r_1 = 3	r_1 = 3
r_2 = 4	r_2 = 4
Synchronous rev. per min. = 1000	Synchronous rev. per min. = 1000
Core loss = 0	Core loss = 0
Performance	Performance
Output horsepower = 51.4619	Output horsepower = 51.4619
Primary amperes = 18.7178	Primary amperes = 18.7178
Torque ft. lb. = 290.137	Torque ft. lb. = 290.137
Rev. per min. = 932.846	Rev. per min. = 932.846
Efficiency = 0.866459	Efficiency = 0.866459
Power factor = 0.789043	Power factor = 0.789043

A comparison of the constants listed under the word "data" in the right and left hand columns will show that the reactances are different both as to symbols and numerical values. The use of different reactances is a result of the fact that the two systems of calculation are based on different methods of analysis, but all of the various reactance values have definite mathematical relations which will be explained below.

V. The Transformer

Fig. 2 shows a transformer with magnetizing and leakage characteristics similar to those of an induction motor. The broken lines represent flux paths.

$\mathcal{P}_m$ = Permeance of the path through both coils

$\mathcal{P}_L'$ = Permeance of the primary leakage path

$\mathcal{P}_L''$ = Permeance of the secondary leakage path.

The most important of the fundamental constants which determine the performance of a transformer or an induction motor may be expressed as ratios between the permeance values.

$$\text{The primary flux factor } K_p = \frac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L'}$$

$$\text{The secondary flux factor } K_s = \frac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L''}$$

VI. Reactance

The reactance of a transformer represents the ratio

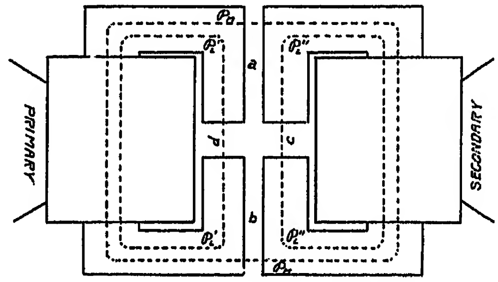


Fig. 2—The Flux Paths of a Transformer with an Air-Gap and Large Magnetic Leakage

of inductive drop to amperes, just as resistance represents the ratio of resistance drop to amperes. In a circuit containing only resistance, the current

$$I = \frac{E}{R}$$

while in a circuit which has reactance without resistance,

$$I = \frac{E}{X}$$

Since the induced e. m. f.

$$E = 2\,\pi\,f\,N^2\,10^{-8}\,\mathcal{P}\,I$$

we may derive the fundamental equation for reactance as follows:

$$I = \frac{2\,\pi\,f\,N^2\,10^{-8}\,\mathcal{P}\,I}{X}$$

and

$$X = 2\,\pi\,f\,N^2\,10^{-8} \times \mathcal{P}$$

It is convenient and helpful to think of this expression for reactance as made up of the two main factors which are separated by a multiplication sign. The combination of symbols on the left, $2\,\pi\,f\,N^2\,10^{-8}$, will be found in exactly the same form in all of the seven equations which appear in the two lists below, while the characters which stand for permeance take a special form in each equation and determine the significance of the various reactances.

A comparison of the permeance values in the first list of equations with those which appear in the second list will show that the reactances are of two fundamentally different types. Each equivalent circuit reactance represents the effect of only a portion of the total flux which passes through the winding and, therefore, is only a *component* of the total reactance. On the other hand, each of the reactance values which make up the second list and are used in the system presented in this paper represents the effect of all the flux and constitutes the total reactance of the winding for the particular condition specified.

Equivalent Circuit Reactances.

Reactance of the primary winding due to the primary leakage flux

$$x_1 = 2\,\pi\, f\, N^2\, 10^{-8}\, \mathcal{P}_L'$$

Reactance of the secondary winding due to the secondary leakage flux

$$x_2 = 2\,\pi\, f\, N^2\, 10^{-8}\, \mathcal{P}_L''$$

Reactance of the primary winding due to the flux which passes through both coils.

$$X_m = 2\,\pi\, f\, N^2\, 10^{-8}\, \mathcal{P}_m$$

Reactance Values Used in This Paper.

Reactance of primary with secondary open.

$$X_o' = 2\,\pi\, f\, N^2\, 10^{-8}\, (\mathcal{P}_m + \mathcal{P}_L')$$

Reactance of secondary with primary open.

$$X_o'' = 2\,\pi\, f\, N^2\, 10^{-8}\, (\mathcal{P}_m + \mathcal{P}_L'')$$

Reactance of primary with secondary short circuited.

$$X_{sc}' = 2\,\pi\, f\, N^2\, 10^{-8}\, (\mathcal{P}_L' + \mathcal{P}_L''\, K_s)$$

Reactance of secondary with primary short circuited.

$$X_{sc}'' = 2\,\pi\, f\, N^2\, 10^{-8}\, (\mathcal{P}_L'' + \mathcal{P}_L'\, K_p)$$

In practical work it is usually assumed that $\mathcal{P}_L' = \mathcal{P}_L''$ and consequently that

$$K_p = K_s$$
$$X_o' = X_o'' = X_o$$
$$X_{sc}' = X_{sc}'' = X$$

A series of diagrams showing the flux paths corresponding to all of the reactance values listed above will be found in Figs. 3 to 9.

From the permeance values, it may easily be demonstrated that

$$X_o' = \frac{X_m}{K_p} \qquad x_1 = X_{sc}'\,\frac{1 - K_p}{1 - K_p\, K_s}$$

$$X_o'' = \frac{X_m}{K_s} \qquad x_2 = X_{sc}''\,\frac{1 - K_s}{1 - K_p\, K_s}$$

$$X_{sc}' = x_1 + x_2\, K_s \qquad = X_{sc}'\,\frac{K_p\,(1 - K_s)}{K_s\,(1 - K_p\, K_s)}$$

$$X_{sc}'' = x_2 + x_1\, K_p \qquad X_m = X_o'\, K_p = X_o''\, K_s$$

VII. Circle Diagram

The development of a mathematically exact form of the circle diagram may be traced through Figs. 10, 11, 12, and 13. These figures are so constructed and arranged as to show successively the effects of the various constants. In Figs. 10 and 11 the motor is assumed to have reactance without resistance or iron loss. Fig. 12 shows the modifying effects of secondary resistance while Fig. 13 shows the modifying effects of primary resistance and core losses.

Fig. 14 is a practical working diagram and is similar to the upper right hand portion of Fig. 13 except that the primary resistance drop is represented by an extension of the current vector instead of a separate parallel line. The complete procedure for making calculations by this diagram is given on the work sheet shown in Fig. 15.

This work sheet is introduced to show how the circle diagram may be used in a correct form for practical

Fig. 3 Fig. 4

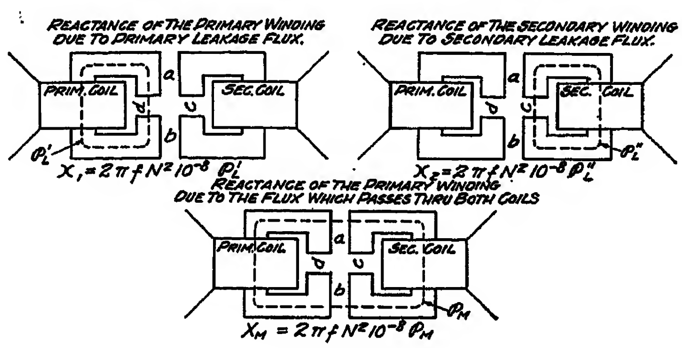


Fig. 5

Figs. 3-5—Reacance Values Used in the Steinmetz System

calculations and also to illustrate the general method of procedure which underlies the much easier process explained in the next section.

The only measurements taken from the diagram are $O\,T$, $M\,T$, $T\,R$, and $Z\,E$ from which we obtain

$$\text{Secondary input} = T\,R \times S_1 \times E \times \text{phases} \left(\frac{O\,E}{Z\,E}\right)^2$$

and the corresponding values of

$$\text{Primary amperes} = O\,T \times S_1 \times \frac{O\,E}{Z\,E}$$

and

$$\text{Secondary amperes} = M\,T \times S_2 \times \frac{O\,E}{Z\,E}$$

When these quantities are known, the completion of the calculation requires only a few operations of simple arithmetic.

Input = Secondary input + primary copper losses + core loss.

Output $=$ Secondary input—(Secondary copper loss $+$ F & W loss)

R. P. M. $=$ Synchronous rev. per min. $\dfrac{\text{Secondary input—Secondary copper loss}}{\text{Secondary input}}$

Efficiency $= \dfrac{\text{Output}}{\text{Input}}$

Power factor $= \dfrac{\text{Input}}{\text{Apparent input}}$

VIII. The Basis of the Curve Method

The outline given below shows a simple and straight forward procedure for the calculation of polyphase

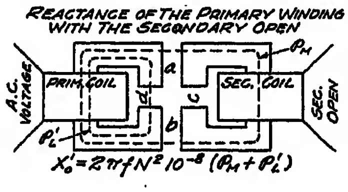


Fig. 6

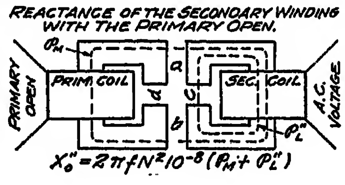


Fig. 7

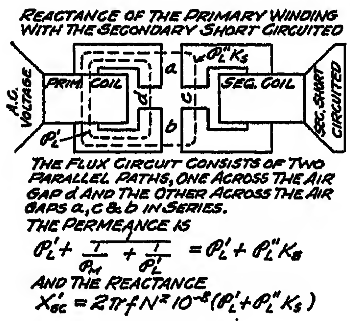


Fig. 8

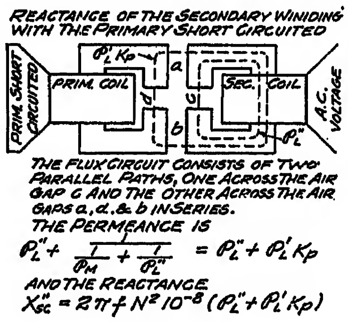


Fig. 9

Figs. 6-9—Reactance Values Used in the System Presented in This Paper

induction motor performance without the circle diagram. This process, or something equivalent, would probably be used by all designers if suitable equations were available for the third and fourth steps.

(1) Torque $= H\,P \dfrac{5252}{\text{Rev. per min.}}$ (Using test or estimated value of rev. per min.)

(2) Secondary input $=$ Torque $\dfrac{\text{Synchronous rev. per min.}}{7.04}$

(3) Primary amperes $=$ Secondary input $\times$ (*No convenient expression available*)

(4) Secondary amperes $=$ Secondary input $\times$ (*No convenient expression available*)

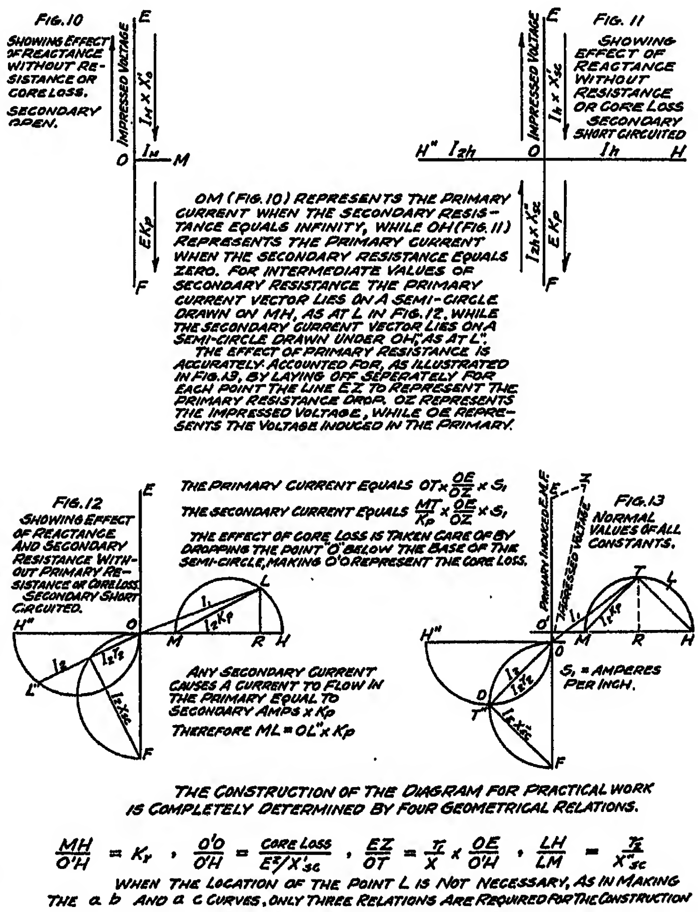
(5) Secondary copper loss $=$ (Secondary amperes)^2 $\times\, r_2 \times$ phases

(6) Secondary output $=$ Secondary input—Secondary copper loss

(7) Output $=$ Secondary output—F and W loss

(8) Rev. per min. $= \dfrac{\text{Secondary output}}{\text{Secondary input}}$ $\times$ synchronous rev. per min.

(9) Primary copper loss $=$ (Primary amperes)^2 $\times\, r_1 \times$ phases



Figs. 10-13—Development of the Circle Diagram

(10) Input $=$ Secondary input $+$ primary copper loss $+$ iron loss

(11) Efficiency $= \dfrac{\text{Output}}{\text{Input}}$

(12) Power factor $= \dfrac{\text{Input}}{\text{Primary amperes} \times E \times \text{phases}}$

Starting with the horsepower for which a calculation is desired, the first step gives the torque while the second gives the input to the rotor. The next quantities wanted are the primary and secondary amperes; but the equations which might be written for these steps would be so elaborate and complicated as to involve many times more work than all the other steps in the calculation combined.

This directs attention to the fact that in any *rigorous*

method of calculating polyphase induction motor performance, after the constants are known, the determination of the current values which correspond to any

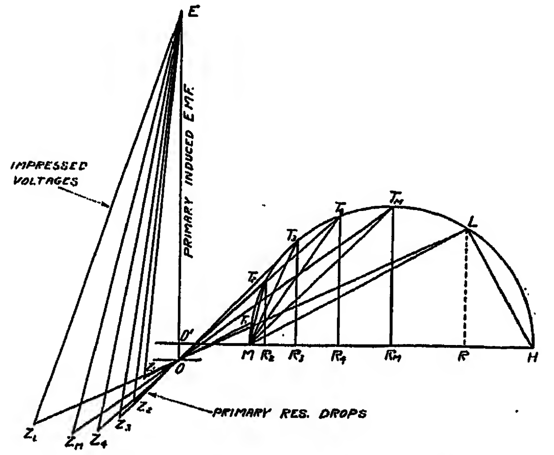


Fig. 14—The Circle Diagram for Practical Work

specified input makes nearly all of the work. In the Circle Diagram processes, these relations are determined graphically, while in the Steinmetz System the

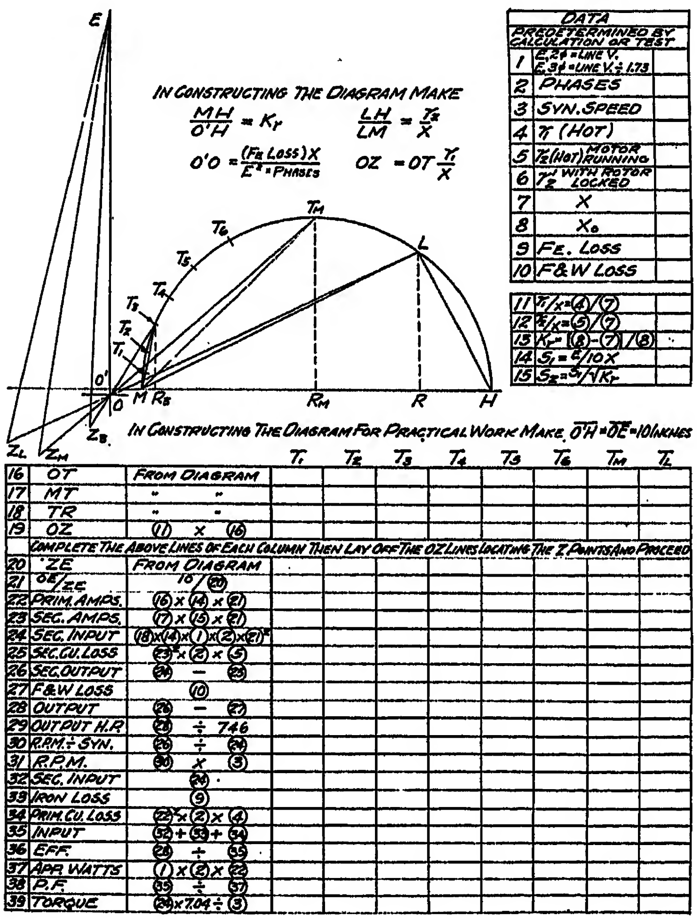


Fig. 15—Worksheet for Calculating Performance by Circle Diagram

results are obtained by lengthy analytical equations.

In the system which this paper describes these tedious and lengthy processes are eliminated. The primary and secondary amperes are obtained with a negligible amount of labor by reference to two sets of curves, reduced examples of which are shown in Figs. 16 and 17.[2] One set, known as the *a b* curves, is used for primary amperes, while the other set known as the *a c* curves, is used for secondary amperes. The values which the curves represent are geometrical relations from the circle diagram shown in Fig. 14, and are mathematical quantities of the same general character as sines or cosines. On both sets of curves the abscissa is marked *a*, while the ordinates are marked *b* on the curves for primary amperes and *c* on the curves for secondary amperes. In terms of the lines on the diagram, in Fig. 14,

$$a = \frac{T\,R}{O'\,H} \times \left(\frac{O\,E}{Z\,E}\right)^2 \text{ and \textit{represents} secondary input}$$

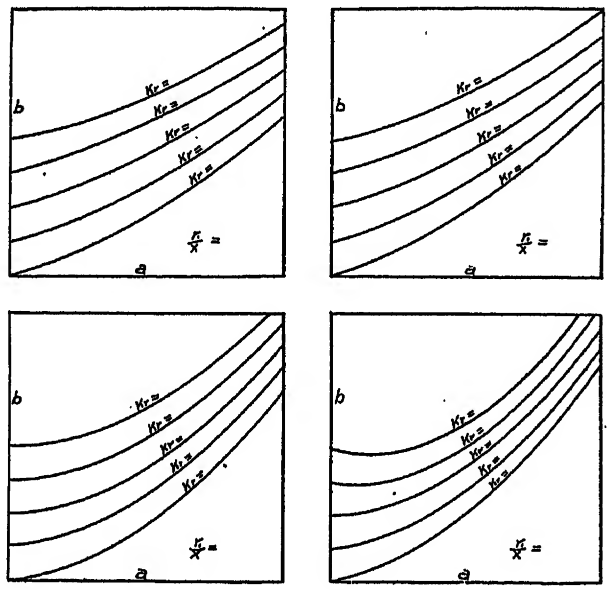


Fig. 16—Examples of *a b* Curves

The most satisfactory scale is 0.02 per in. for ordinates and abscissas See Fig. 17A

$$b = \frac{O\,T}{O'\,H} \times \frac{O\,E}{Z\,E} \text{ and \textit{represents} primary amperes}$$

$$c = \frac{M\,T}{O'\,H \times K_p} \times \frac{O\,E}{Z\,E} \text{ and \textit{represents} secondary amperes}$$

while in terms of the motor values,

$$a = \frac{\text{Secondary input}}{(E^2/X) \times \text{phases}}$$

$$b \times \frac{E}{X} = \text{primary amperes}$$

$$c \times \frac{E}{X} = \text{secondary amperes}$$

2. The author expects to make available in the near future two ful lsets of curves which cover about 100 pages.

In a practical calculation, we complete the first and second items of the procedure outlined above and then obtain

$$a = \frac{\text{Secondary input}}{(E^2/X)\ \text{phases}}$$

Next using a as abscissa we read b and c from the appropriate curves and as stated above

$$b \times \frac{E}{X} = \text{primary amperes}$$

$$c \times \frac{E}{X} = \text{secondary amperes}$$

IX. Description of the Curve Sheets

In preparing the $a\,b$ and $a\,c$ curves, we take advantage of the fact that the geometrical construction of the circle diagram is determined by three constants.

If the voltage and current scales are so chosen as to make the lines $O\,E$ and $O'\,H$ (Fig. 14) of equal length, the only relations involved in the construction are

$$\frac{M\,H}{O'\,H} = \frac{X_o - X}{X_o} = K_p\,K_s = K_r$$

$$\frac{O\,Z}{O\,T} = \frac{r_1}{X}$$

$$\frac{O'\,O}{O'\,H} = \frac{\text{Core loss}}{(E^2/X)\ \text{phases}}$$

The general scheme of the $a\,b$ curves is illustrated by Fig. 16. All of the curves give the values of b corresponding to the variations in the value of a over as wide a range as practical work requires. Each individual curve relates to a particular set of constants, such as

$$K_r = 0.92$$

$$\frac{r_1}{X} = 0.3$$

$$\frac{F_e\,X}{E^2 \times \text{phases}} = 0.005$$

The various curves on one sheet relate to different values of K_r but to the same values of the other constants, while each sheet relates to a different value of r_1/X.

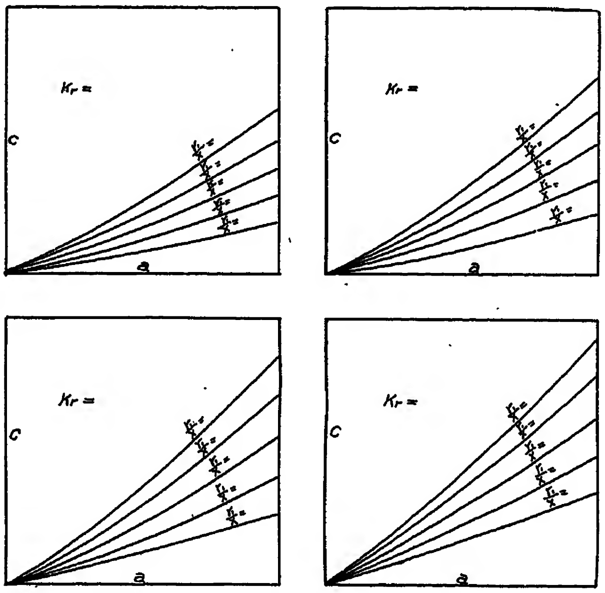


Fig. 17—Examples of $a\,c$ Curves

See Fig. 17a

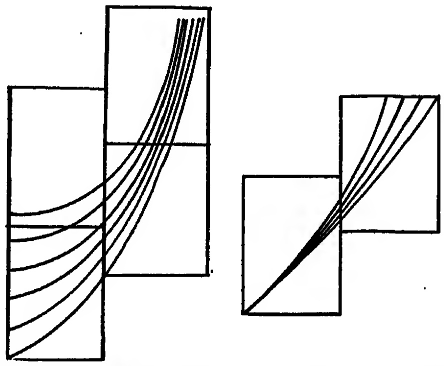


Fig. 17a—Method of Arranging Curves on Cross-Section Sheets

The most satisfactory scale for the $a\,b$ and $a\,c$ curves is 0.02 per in. for both abscissas and ordinates If the common 7-in. by 10-in. cross-section paper is used each group of $a\,b$ curves may be plotted on four sheets as shown above and each group of $a\,c$ curves may be plotted on two sheets as shown

To make the system logically complete it would be necessary to go a step further and make a separate set of curve sheets for each of a series of values of the third constant $\frac{F_e\,X}{E^2 \times \text{phases}}$. Such elaboration, however, is not necessary. The core loss affects the primary amperes to only a slight extent and as high a degree of accuracy as it is possible to utilize in slide rule work may be obtained by using for all the curves a mean value of $\frac{F_e\,X}{E^2 \times \text{phases}}$ and making an approximate compensating correction when the actual value differs appreciably from that on which the curves are based.

Therefore all the $a\,b$ curves are based on the assumption that $\frac{F_e\,X}{E^2 \times \text{phases}} = 0.005$ and the correction consists in adding algebraically to the value of a which is used as abscissa for the $a\,b$ curve the quantity

$$\left(\frac{F_e\,X}{E^2 \times \text{phases}} - 0.005\right) 0.6$$

When this correction has been applied, the discrep-

ancy in the primary ampere figures will not often exceed one-tenth of one per cent.

Since $\dfrac{F_e X}{E^2 \times \text{phases}}$ has no effect on the secondary amperes, it does not have to be considered in connection with the $a\,c$ curves, which are plotted as illustrated by Fig. 17. The difference between the methods of

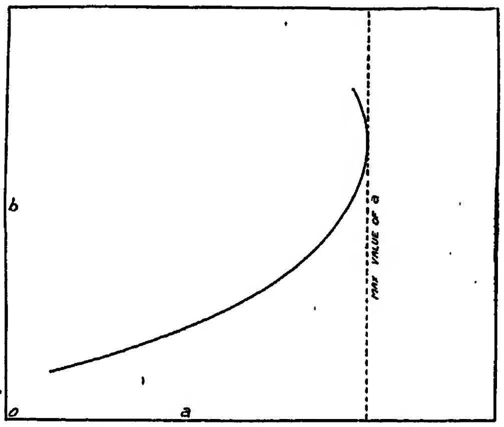


FIG. 18—AN $a\,b$ CURVE, SHOWING THE MAXIMUM VALUE OF a

plotting the two sets of curves is simply a matter of convenience. If the a-c. curves were plotted like the $a\,b$, the lines would be too close together.

X. METHOD OF CALCULATING VALUES FOR THE CURVES

In preparing the $a\,b$ and $a\,c$ curves, it is possible to save labor as well as to secure greater accuracy by

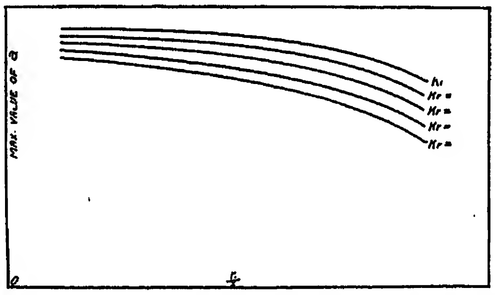


FIG. 19—ILLUSTRATING CURVES FOR DETERMINATION OF MAXIMUM TORQUE

deriving the values analytically instead of graphically. The equations and work sheets for two different methods will be found in the Appendix.

XI. MAXIMUM TORQUE

All of the $a\,b$ curves, if completely drawn, have the general shape illustrated by Fig. 18. In other words, the value of a, which represents torque, goes up to a maximum and then falls off. This suggests a convenient method of calculating the maximum torque.

It is only necessary to find the maximum value of a on each $a\,b$ curve and plot the results as illustrated in Fig. 19. Then the maximum torque

$$T \text{ maximum} = a \text{ (maximum)} \times \frac{E^2 \times 7.04 \times \text{phases}}{X \times \text{synchronous r.p.m.}}$$

Maximum torque curves of this character have not actually been made up to the present time.

XII. PRACTICAL PROCEDURE BY THE CURVE METHOD

Full directions for making performance calculations from known constants will be found on the work sheet, Fig. 20.

A desirable feature of this system lies in the fact that the output which a calculation will give is known in advance with a high degree of accuracy. Consequently

DATA		
PREDETERMINED BY CALCULATION OR TEST		
1	E, 2φ = LINE V. E, 3φ = LINE V. ÷ 1.73	1000
2	PHASES	3
3	SYN. SPEED	1000
4	r_1 (HOT)	3
5	r_2 (HOT)*	4
6	r_2'**	
7	X	10
8	X_0	100
9	FE LOSS	400
10	F & W LOSS	700
FULL LOAD READINGS FROM TEST		
11	R.P.M.	
12	F.L. AMPS.	
13	F.L. WATTS	

PRELIMINARY CALCULATIONS			
14	r_1/x	(4) ÷ (7)	.3
15	r_2/x	(6) ÷ (7)	.4
16	K_r	((8) − (7)) ÷ (8)	.9
17	E/x	(1) ÷ (7)	100
18	E^2/x	(17) × (1)	100000
19	$F_E X / E^2 \times$ PHASES	(9) × (7) ÷ (1)² (2)	.004
20	CORRECTION	((19) − .005) × .6	−.0006
21	F.L.T.	(5252 × H.P.) ÷ (11)	282

* THE SECONDARY RESISTANCE CANNOT BE DIRECTLY DETERMINED BY TEST. IT CAN BE DETERMINED ACCURATELY ONLY FROM THE SLIP. THE CORRECT VALUE OF r_2 IS THAT FROM WHICH THE CORRECT SPEED AS SHOWN BY ITEM 11 CAN BE CALCULATED.

TAKE A TRIAL VALUE OF r_2 AND CARRY THE CALCULATIONS DOWN ONLY TO ITEM 43 THEN

r_2 (CORRECT) = r_2 (TRIAL VALUE) × $\dfrac{\text{OBSERVED SLIP}}{\text{CALCULATED SLIP}}$

ERASE ITEMS 5, 37, 42 AND 43; RECALCULATE USING THE CORRECT VALUE OF r_2.

WHEN THE CONSTANTS HAVE BEEN CALCULATED USE THE CALCULATED VALUE OF r_2 IN DETERMINING THE SLIP. THE SECONDARY RESISTANCE USED FOR STARTING TORQUE, r_2', HAS A SOMEWHAT HIGHER VALUE WHICH CANNOT BE CALCULATED, EXCEPT APPROXIMATELY BY EMPIRICAL METHODS.

** FROM LOCK READINGS.

† ITEMS 29 AND 30 MUST BE ADDED ALGEBRICALLY.

27	TORQUE	(H.P. × 5252) ÷ R.P.M.			282			
28	SEC. INPUT PER φ	[((27) × (3)) ÷ 7.04] + (10)) ÷ (2)			13600			
29	(a) UNCORRECTED	(28) ÷ (18)			.1360			
30	CORRECTION	(20)			−.0006			
31	(a) CORRECTED	(29) + (30) †			.1354			
32	(b)	FROM CURVE—(31) AS ABSCISSA			.1879			
33	PRIM. AMPS.	(32) × (17)			18.79			
34	(c)	FROM CURVE—(29) AS ABSCISSA			.1522			
35	SEC. AMPS.	(34) × (17)			15.22			
36	SEC. INPUT	(28) × (2)			40800			
37	SEC. CU. LOSS	(35)² × (5) × (2)			2780			
38	SEC. OUTPUT	(36) − (37)			38020			
39	F & W LOSS	(10)			700			
40	OUTPUT WATTS	(38) − (39)			37320			
41	OUTPUT H.P.	(40) ÷ 746			50			
42	R.P.M. ÷ SYN.	(38) ÷ (36)			.932			
43	R.P.M.	(42) × (3)			932			
44	SEC. INPUT	(36)			40800			
45	FE LOSS	(9)			400			
46	PRIM. CU. LOSS	(33)² × (4) × (2)			3175			
47	INPUT WATTS	(44) + (45) + (46)			44375			
48	EFF.	(40) ÷ (47)			.843			
49	APP. WATTS	(1) × (33) × (2)			56450			
50	P.F.	(47) ÷ (49)			.785			

FIG. 20—WORKSHEET FOR CALCULATING PERFORMANCE BY USE OF $a\,b$ AND $a\,c$ CURVE SHEETS SHOWN IN FIGS. 16 AND 17

when the efficiency, power factor, etc., for rated load are wanted, it is not necessary to go through the calculation two or three times in order to obtain figures for the correct output. This is due to the fact that the calculation begins with the torque which can be determined precisely for any specified load when the speed is known. For example, in the illustrative calculation given on the work sheet, the speed obtained by test is 932 rev. per min. Therefore, the torque for 50 hp. is

$$\frac{50 \times 5252}{932} = 282 \text{ ft. lb.}$$

and starting with 282 ft. lb. in line 27, we obtain in line 41 an output of exactly 50 hp.

When it is necessary to estimate the speed, the error

in the assumed full load torque and consequently the discrepancy between the calculated output and the rated horsepower will be the same in percentage as the error which is made in estimating the speed. From an inspection of the motor constants it is usually possible to estimate the full load speed without an error of more than about ½ per cent. Therefore, without knowing the test value of rev. per min. we could have made the output come within ½ per cent of the rated horsepower, that is between 49.75 hp. and 50.25 hp.

This result should be compared with the wide dis-

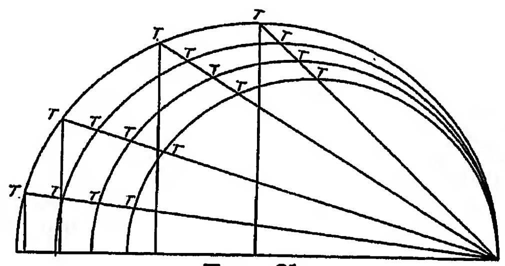


FIG. 21

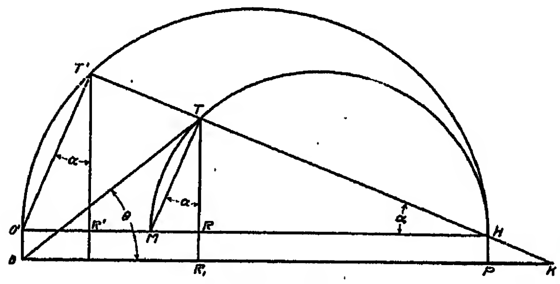


FIG. 22

FIGS. 21-22—CIRCLE DIAGRAMS TO ILLUSTRATE THE ANALYTICAL DERIVATION OF $a\,b$ AND $a\,c$ CURVES, FIRST METHOD

crepancies which occur with the Steinmetz system, in which just as in the procedure presented above, the first step is an estimate of the full load rev. per min. In the Steinmetz procedure the estimated speed is used to determine not the torque but the slip.

The calculation begins with the slip and the output obtained is that at which the estimated slip would occur. For example, taking the same figures used above, if the estimate of the speed is ½ per cent high or low the slip used in the calculation will be, 1000 − 927 = 73 which is 7 per cent high, or 1000 − 937 = 63 which is 7 per cent low, and the output obtained may be as low as 46½ hp. or as high as 53½ hp.

Appendix

A complete set of $a\,b$ curves has been prepared by the author covering 56 pages and including values of r_1/X from 0.1 to 1.

A complete set of $a\,c$ curves has been prepared covering 48 pages and including values of K_r from 0.98 to 0.75 inclusive. Both sets of curves may, of course, be expanded to any extent that is found desirable.

The formulas and work sheets for two processes by which the curves may be calculated without graphical work are given below. The process given first is the best for calculating a complete set of curves at one time, while the second process is more convenient when a single curve is to be made for a special motor.

ANALYTICAL DERIVATION OF $a\,b$ AND $a\,c$ CURVES
First method

In this process the T points are located as shown in Fig. 21 which represents the diagrams for several K_r values superimposed. This arrangement makes the angle $T\,H\,O$ the same for corresponding T points on all diagrams.

With the T points so located:

$$\overline{T\,R} = \overline{T'\,R'}\,K_r \text{........Fig. 22}$$

$$\overline{M\,T} = \overline{O'\,T'}\,K_r$$

$$\overline{O\,T} = \sqrt{1 - 2\,A\,K_r + B\,K_r^2}$$

1	T'R'	ASSUME	.02500	.05000	.10000	.15000	.200
2	SIN 2α	2×(1)	.05000	.10000	.20000	.30000	.40
3	2α		2°52'00"	5°44'21"	11°32'13"	17°27'28"	23°34
4	α		1°26'00"	2°52'10.5	5°46'6.5	8°43'44"	11°47
5	SIN α		.02500	.05006	.10051	.15176	.204
6	COS α		.99969	.99875	.99494	.98842	.978
7	HK	.005/(5)	.19998	.09988	.04975	.03295	.024
8	T'H	(1)/(5)	.99988	.99878	.99494	.98846	.97
9	PK	(6)×(7)	.19991	.09975	.04950	.03256	.023
10	R'H	(6)×(8)	.99956	.99753	.98990	.97702	.95
11	OK	1+(9)	1.19991	1.09975	1.04950	1.03256	1.023
12		(10)×(11)	1.19939	1.09704	1.03890	1.00883	.98
13		(7)×(8)	.19995	.09976	.04950	.03257	.023
14	A	(12)−(13)	.99944	.99728	.98940	.97626	.957
15	B	(8)²	.99978	.99756	.98990	.97706	.95
16	O'T'	(1)/(6)	.02501	.05006	.10051	.15176	.204
17	MT	K_r×(16)					
18	TR	K_r×(1)					
19	OO'	.005					
20	TR₁	(18)+(19)					
21	2 OT SIN θ	2×(20)					
22	1+B×K_r^2	K_r^2×(15)+1.0					
23	2AK_r	2K_r×(14)					
24	$\overline{OT}^2$	(22)−(23)					
25	OT	√(24)					
26	2 OZ SIN θ	r_1/X×(21)					
27	$\overline{OZ}^2$	$(r_1/X)^2$×(24)					
28	$\overline{ZE}^2$	(26)+(27)+1.0					
29	$(OZ/ZE)^2$	1/(28)					
30	OZ/ZE	√(29)					
31	a	(29)×(18)					
32	b	(30)×(25)					
33	c	(30)×(17)÷K_r					

FIG. 23—WORKSHEET FOR CALCULATING $a\,b$ AND $a\,c$ CURVES, FIRST METHOD

A separate calculation of items 17-25 is made for each value of K_r. A separate calculation of items 26-33 is made for each curve

The expression under the radical is derived as follows:

$$\overline{O\,T}^2 = \overline{O\,K}^2 + \overline{T\,K}^2 - 2\,\overline{O\,K} \times \overline{T\,K} \cos \alpha$$

But

$$\overline{T\,K} = \overline{T\,H} + \overline{H\,K} \text{ and } \overline{T\,K} \cos \alpha = \overline{R_1\,K} = \overline{R\,H} + \overline{P\,K}$$

$$\therefore \overline{O\,T}^2 = \overline{O\,K}^2 + \overline{T\,H}^2 + 2\,\overline{T\,H} \times \overline{H\,K} + \overline{H\,K}^2 - 2\,\overline{O\,K} \times \overline{R\,H} - 2\,\overline{O\,K} \times \overline{P\,K}$$

$$= (\overline{O\,K}^2 - 2\,\overline{O\,K} \times \overline{P\,K} + \overline{H\,K}^2) - 2\,(\overline{O\,K} \times \overline{R\,H} - \overline{T\,H} \times \overline{H\,K}) + \overline{T\,H}^2$$

The first term of the last expression above is very nearly equal to $O'\,H$ which is represented by unity. Its actual value is approximately 1.000025. Therefore it may be assumed that

$$\overline{O\,K}^2 + \overline{H\,K}^2 - 2\,\overline{O\,K} \times \overline{P\,K} = 1.0000\ldots.$$

The second term, $(\overline{O\,K} \times \overline{R\,H} - \overline{T\,H} \times \overline{H\,K})$ is

proportional to K_r. If $(\overline{OK} \times \overline{RH} - \overline{TH} \times \overline{HK}) = A$ when K_r = unity, then for any other value of K_r

$$\overline{OK} \times \overline{RH} - \overline{TH} \times \overline{HK} = A \times K_r$$

The last term, $\overline{TH}^2$, is proportional to K_r^2. If $\overline{TH}^2 = B$ when K_r = unity, then for any other value of K_r

$$\overline{TH}^2 = B \times K_r^2$$

For a given value of $T'\,R'$ the angle α is found from the following relation:

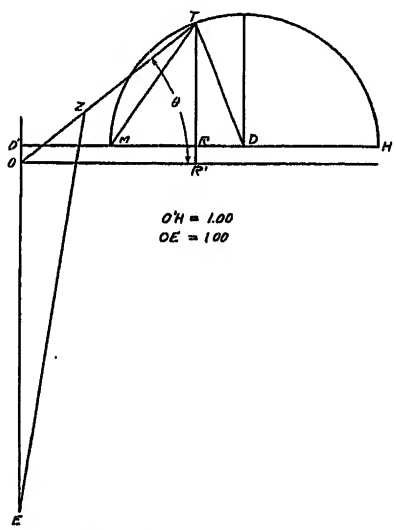


Fig. 24—Circle Diagram to Illustrate the Analytical Derivation of $a\,b$ and $a\,c$ Curves, Second Method

$$\text{Angle } M\,T\,R = \text{Angle } R\,H\,T = \alpha$$

$$\cos\alpha = \frac{T'\,R'}{O'\,T'};\ \sin\alpha = \frac{O'\,T'}{O'\,H} = O'\,T' \text{ since } O'\,H = 1$$

$$\sin\alpha\cos\alpha = T'\,R' = \frac{\sin 2\,\alpha}{2} \quad \therefore \sin 2\,\alpha = 2\,T'\,R'$$

This explanation covers lines 1-25 of the calculation sheet. The remaining lines relate to the same process as lines 25-36 of the second method.

Analytical Derivation of $a\,b$ and $a\,c$ Curves
Second Method

(1) To obtain $O\,T$

$$\overline{RD}^2 = \overline{TD}^2 - \overline{TR}^2$$
$$\overline{RD}^2 = \overline{MD}^2 - \overline{TR}^2$$
$$\overline{RD} = \sqrt{\overline{MD}^2 - \overline{TR}^2}$$
$$\overline{O'R} = \overline{OR'} = \overline{O'H} - (.5\,K_r + \overline{RD})$$
$$\overline{OT} = \sqrt{\overline{OR'}^2 + \overline{TR'}^2}$$

(2) To obtain $\overline{MT}$

$$\overline{MR} = .5\,K_r - \overline{RD}$$
$$\overline{MT} = \sqrt{\overline{TR}^2 + \overline{MR}^2}$$

(3) To obtain $\overline{ZE}$

$$\overline{OZ} = \overline{OT} \times r_1/X$$

$$\overline{ZE} = \sqrt{\overline{OE}^2 + \overline{OZ}^2 - 2\,\overline{OE} \times \overline{OZ} \times \cos E\,O\,Z}$$
$$= \sqrt{1 + \overline{OZ}^2 - 2\,\overline{OZ} \times \cos E\,O\,Z}$$
$$= \sqrt{1 + \overline{OZ}^2 + 2\,\overline{OZ} \times \sin R'\,O\,T}$$
$$\overline{ZE} = \sqrt{1 + \overline{OZ}^2 + 2\,\overline{OZ}\left(\frac{T\,R'}{O\,T}\right)}$$

(4) $$a = \overline{TR} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right)^2 = \overline{TR} \times \left(\frac{1}{Z\,E}\right)^2$$

$$b = \overline{OT} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right) = \overline{OT} \times \left(\frac{1}{Z\,E}\right)$$

$$c = \overline{MT} \times \left(\frac{\overline{OE}}{\overline{ZE}}\right) \div K_p = \overline{MT} \times \left(\frac{1}{\overline{ZE}}\right) \div K_p$$

1	K_r	
2	r/x	
3	K_p	$\sqrt{1}$
4	$.5K_r$	$.5 \times 1$
5	TR	ASSUME
6	O'O	
7	TR + O'O	5 + 6
8	$\overline{.5K_r}^2$	4^2
9	$\overline{TR}^2$	5^2
10	$\overline{RD}^2$	8 − 9
11	$.5K_r$	4
12	RD	$\sqrt{10}$
13	MR	11 − 12
14	$\overline{MR}^2$	13^2
15	$\overline{TR}^2$	9
16	$\overline{MT}^2$	14 + 15
17	MT	$\sqrt{16}$
18	1.0	1.000
19	RH	11 + 12
20	OR'	18 − 19
21	$\overline{OR'}^2$	20^2
22	$\overline{TR + O'O}^2$	7^2
23	$\overline{OT}^2$	21 + 22
24	OT	$\sqrt{23}$
25	OZ	24 × 2
26	SIN θ	7/24
27	2 × OZ × SIN θ	2 × 25 × 26
28	$\overline{OZ}^2$	25^2
29	1.0	1.000
30	$\overline{ZE}^2$	27 + 28 + 29
31	ZE	$\sqrt{30}$
32	$\frac{OE}{ZE}$	1/31
33	$\left(\frac{OE}{ZE}\right)^2$	32^2
34	a	5 × 33
35	b	24 × 32
36	c	7 × 32 ÷ 3

Fig. 25—Work Sheet for Calculating $a\,b$ and $a\,c$ Curves by Second Method

Table of Symbols

a	=	Abscissa for the $a\,b$ and $a\,c$ curves.
b	=	Ordinate of $a\,b$ curve.
c	=	Ordinate of $a\,c$ curve.
E	=	Voltage. (Line voltage for two phase and line voltage ÷ 1.73 for three phase.)
f	=	Frequency.
F_e	=	Iron loss in watts.
F & W	=	Friction and windage loss.
F. L. T.	=	Full load torque.
I	=	Amperes.
I_1	=	Primary amperes.
I_2	=	Secondary amperes, assuming 1 to 1 ratio.
I_m	=	Magnetizing amperes.
I_h	=	Primary locked amperes, when resistances equal zero.

I_{2h} = Secondary locked amperes when resistances equal zero.

K_p = Flux factor = $\dfrac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L'}$

K_s = Flux factor $\dfrac{\mathcal{P}_m}{\mathcal{P}_m + \mathcal{P}_L''}$

K_r = Flux factor = $K_p \times K_s$

N = Number of turns.

$\mathcal{P}$ = Permeance, as defined by Karapetoff. $\mathcal{P} = 3.19 \dfrac{\text{Area}}{\text{Length}}$ for an air gap.

$\mathcal{P}_m$ = Permeance of the flux path through both primary and secondary coils.

$\mathcal{P}_L'$ = Permeance of the primary leakage path.

$\mathcal{P}_L''$ = Permeance of the secondary leakage path.

r = Resistance.

r_1 = Primary resistance.

r_2 = Secondary resistance, assuming a 1 to 1 ratio.

r_2' = Effective secondary resistance of an induction motor under the condition of locked readings, assuming a 1 to 1 ratio.

R = Combined effective resistance of stator and rotor under the condition of locked readings, = locked watts ÷ (primary amperes)^2.

R.... See equivalent circuit, Fig. 1.

r_f.... See equivalent circuit, Fig. 1.

S_1 = Primary amperes per inch on circle diagram.

S_2 = Secondary amperes per inch = $S_1 \div K_p$.

x = Reactance.

x_1 = Reactance of primary winding due to primary leakage flux.

x_2 = Reactance of secondary winding due to secondary leakage flux.

X_m = Reactance of primary winding due to the flux which cuts both coils.

X = Reactance—Either X_{sc}' or X_{sc}'' when the two are assumed to be equal.

X_o = Either X_o' or X_o'' when the two are assumed to be equal.

X_o' = Reactance of the primary with the secondary open, when resistances equal zero.

X_o'' = Reactance of the secondary with the primary open, when resistances equal zero.

X_{sc}' = Reactance of the primary with the secondary short circuited, when resistances equal zero.

X_{sc}'' = Reactance of the secondary with the primary short circuited, when resistances equal zero.

Discussion

A. D. Moore: The complete and correct analytical method of polyphase induction motor performance calculation is very tedious. The accurately-drawn circle diagram involves laborious methods, and it usually includes inherent inaccuracy due to simplifying assumptions made. The Branson method is very simple and easy to use.

To gain advantage a price is usually paid. The user of this method is freed from the price, for the author has already covered that feature by having done the labor of preparing a complete presentation and system of curves. The advantages are two: speedy calculations, and inherent errors minimized to the degree where they are entirely negligible.

A. M. Dudley: Three times in a period of 18 years have I been deeply stirred with a sense of witnessing a distinct advance in the art of calculation and design. The first of these was in 1912 when Mr. Branson presented his Boston paper covering a method of calculating the performance of single-phase motors; the second was at Atlantic City in 1918 when Mr. C. L. Fortescue presented his paper on a *Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks*, and the third is the paper which we have before us at the present time. Several years ago I was associated with Mr. Branson in commercial work on induction motor design and discussed with him his idea of working out in curve form several of the significant relations in the circle diagram which would permit very rapid evaluation of single load points in the calculation of motor performance. As well as I can in a few words I should like to give my estimate of what Mr. Branson has done and its probable value to commercial designers of induction motors.

As is well known to the fraternity the calculation of leakage reactance and iron losses are two of the time consuming items in induction motor calculation. Neither Mr. Branson nor anyone else can obviate this since it is inherent in the problem. However, having established the constants of the motor either by calculation or test readings this paper reduces to a startling extent the further work of reducing these readings to speed-torque and power factor and efficiency curves. It has taken Mr. Branson and his associates several years to produce the required number of a, b, and c curves to which he refers but now that they are produced they become of intense interest to all students and engineers who are working with induction motor calculations. I think it would not be extravagant to say that if a man spent 15 years on this kind of work the use of Mr. Branson's methods ought to add from 1 to 2 years to his working usefulness simply through the item of time saving.

Any discussion of Mr. Branson's paper would be incomplete without reference to the exactness and scientific vigor of his methods. His method of considering the circle diagram seems to me the most exact of all those with which I am familiar and his results are therefore dependable to an extraordinary degree of accuracy.

It is also true that those relations chosen as significant such as K_r, $\dfrac{r_1}{X}$, and $\dfrac{F_s X}{E_2 X \text{ Phases}}$ are those which lend themselves best to the reduction to curve form and make possible the simplicity of the method.

To sum up I feel that in this paper Mr. Branson contributes a new and very useful idea in the field of induction motor calculation. I feel that the method is accurate and time saving. In contributing the a, b, c curves, which he says he proposes to, Mr. Branson is putting at the disposal of all engineers who are interested, the result of several years of painstaking and arduous labor and for this I wish to thank him as one engineer who has profited through the use of this system.

W. J. Morrill: Mr. Branson has spoken of his method as if it were a circle diagram method but in reality it is an entirely new method. He could have used some other scheme for obtaining the data with which he plots his charts. For example, he could have employed the equivalent circuit in Fig. 1 herewith, which represents exactly the current and output which he obtains, and almost exactly the input watts. Mr. Branson assumes

the core loss to be constant. In the equivalent circuit which I show it is represented by the watts lost in the resistance R_e and is not quite constant.

I am very much pleased with Mr. Branson's method because of the straightforward manner with which it solves the designer's problem. By the use of his charts it is possible to proceed directly to the determination of all the motor characteristics corresponding to a given output.

C. R. Boothby and C. G. Veinott: The author is to be highly commended for developing the calculating method given in this paper. Undoubtedly, once such curves as these have

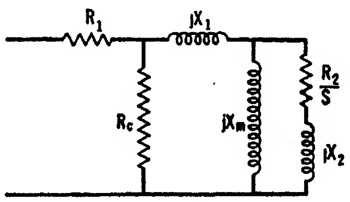


FIG. 1—EQUIVALENT CIRCUIT FOR CURRENT OBTAINED BY BRANSON'S METHOD

been made available, as the author proposes, their use should save much time where a large number of routine calculations is to be made. It is our opinion, however, that while the author has arrived at an admirable calculating method, his development of this method is rather obscure and might lead one to erroneous conclusions. For example, the author states in Fig. 12 "Any secondary current causes a current to flow in the primary equal to secondary amperes times K_p." This means that the component of the primary current which balances the secondary current differs from the secondary current by an amount depending upon the leakage coefficient, K_p.

The foregoing statement is evidently an attempt to justify the division of the chord $M\ T$ by K_p in order to obtain the actual secondary current. There can be no doubt as to the correctness of this procedure as Mr. Behrend, in his book, "The Induction Motor," p. 27, gives the same diagram used by Mr. Branson and shows that when the flux diagram is replaced by the current diagram the chord $M\ T$ becomes $I_2 \times K_p$.

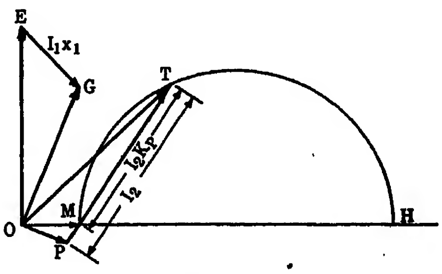


FIG. 2

$O\ G$ voltage impressed across Xm
$O\ P$ magnetizing current under load conditions
$O\ M$ no-load magnetizing current

An inspection of the equivalent circuit discloses one fact which is not apparent from the author's circle diagram. It is that the magnetizing current of the motor decreases with an increase in load. In the diagram the magnetizing current is represented as constant for all loads and $I_2 \times K_p$ is added to it to obtain the primary current. However, that the two systems of treatment give identical results has been illustrated by the author by a specific numerical example. The agreement of the two systems can also be shown by a general algebraic proof. For those who are interested, such a demonstration is given at the end of this discussion.

For those who do not care to follow the detailed mathematical work, we are attempting in Fig. 2 herewith to show graphically the equivalence of these two methods in a clearer, though less rigorous manner. This figure shows how the voltage across the magnetizing reactance, X_m, decreases and changes in phase under load due to the voltage drop in the primary leakage reactance. This voltage is represented by $O\ G$ in this figure. The magnetizing current, that is, the current flowing through X_m, is proportional to this voltage and lags it by 90 deg. This current is represented by $O\ P$. $O\ T$ and $P\ T$ represent the primary and secondary currents, respectively. That the secondary current is larger than the chord of the circle is evident from this figure. That the ratio of the latter to the former is equal to K_p, while not directly evident from the figure, is, however, amply shown both by Mr. Behrend from an analysis of the flux conditions in the motor and also by the complex algebra of the equivalent circuit as given at the end of this discussion.

It may also be well to call attention to the fact that the voltage $O\ D$ in Fig. 13 is actually $\dfrac{I_2\, r_2}{S}$ (S = the slip) instead of $I_2\, r_2$ as shown.

The author is to be highly commended for the detailed "work-sheet" he has given. This makes it possible to apply the method even if the details of the theory are unknown or forgotten. We should like to offer as a suggestion that the curves in Figs. 16 and 17 might be more useful if plotted on log-log paper as this would enable them to be read with the same percentage of accuracy throughout their entire range.

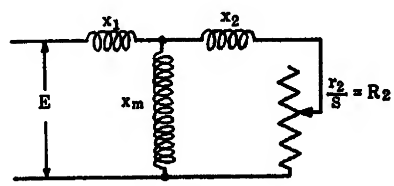


FIG. 3

Comparison of the Circle Diagram with the Equivalent Circuit. The circle diagram given by the author depends for its correctness upon the truth of the equation

$$\check{I}_{mo} + \check{I}_2\, K_p = \check{I}_1{}^* \tag{1}$$

where $\check{I}_{mo}$ = no load magnetizing current $= \dfrac{-j\,E}{X_m + X_1}$ (2)

Let us investigate the truth of Equation (1) by determining $\check{I}_1$ and $\check{I}_2$ from an analysis of the equivalent circuit in which iron loss and primary resistance are neglected. Such a circuit is given in Fig. 3 herewith.

First let us solve for $\check{I}_2$. Applying Kirchoff's laws to the network of reactances and resistances in Fig. 3 the following solution for $\check{I}_2$ is obtained.

$$\check{I}_2 = \frac{E}{\left[\, j\,X_1 + \left(\dfrac{j\,X_1}{j\,X_m} + 1\right)\left(R_2 + j\,X_2\right)\right]} \tag{3}$$

$$= \frac{E}{R_2 + j\left(X_2 + \dfrac{X_1\,X_m}{X_m + X_1}\right)} \times \frac{X_m}{X_m + X_1} \tag{4}$$

Certain groups of constants in the above expression can be recognized as the author's "equivalent" constants so that, from (4)

$$\check{I}_2 = \frac{E\,K_p}{R_2 + j\,X_{so}''} \tag{5}$$

*The sign ˇ over quantity indicates a vector.

Digressing from the main subject for a moment, we think it interesting and worth while to remark that it is evident from Equation (5) that the locus of the secondary current, as R_2 is varied, is a semicircle having a diameter of $\dfrac{E\,K_p}{X_{sc}''}$. This checks the author's secondary current circle in Fig. 12.

But, returning to our main object,

$$\check{I}_2\,K_p = \frac{E\,K_p^2}{R_2 + j\,X_{sc}''} = E\left(\frac{K_p^2\,R_2}{R_2^2 + X_{sc}''^2} - j\,\frac{K_p^2\,X_{sc}''}{R_2^2 + X_{sc}''^2}\right) \tag{6}$$

Now, we can evaluate the left member of Equation (1) by taking the value of $\check{I}_{mo}$ from Equation (2) and adding to Equation (6), obtaining

$$\check{I}_{mo} + \check{I}_2 K_p = E\left[\frac{K_p^2\,R_2}{R_2^2 + X_{sc}''^2} - j\left(\frac{K_p^2\,X_{sc}''}{R_2^2 + X_{sc}''^2} + \frac{1}{X_m + X_1}\right)\right]$$

which reduces to

$$\check{I}_{mo} + \check{I}_2\,K_p = E\left[\frac{K_p^2\,R_2}{R_2^2 + X_{sc}''^2} - j\,\frac{R_2^2 + X_{sc}''\,(X_{sc}'' + K_p\,X_m)}{(R_2^2 + X_{sc}''^2)\,(X_m + X_1)}\right] \tag{7}$$

Now, let us solve directly for $\check{I}_1$ from the equivalent circuit. It is evident from Fig. 3 that

$$\check{I}_1 = \frac{E}{j\,X_1 + \dfrac{j\,X_m\,(R_2 + j\,X_2)}{R_2 + j\,X_2 + j\,X_m}}$$

which reduces to

$$\check{I}_1 = E\,\frac{R_2 + j\,(X_m + X_2)}{-\,X_2\,(X_m + X_1) - X_m\,X_1 + j\,R_2\,(X_m + X_1)} \tag{8}$$

By again noting certain relations between the constants in Equation (8) and the author's equivalent constants, Equation (8) may be reduced, with a little manipulation, to

$$\check{I}_1 = \frac{-\,E\,K_p}{X_m}\;\frac{R_2 + j\,(X_m + X_2)}{(X_{sc}'' - j\,R_2)} \tag{9}$$

This equation, when rationalized, becomes

$$\check{I}_1 = E\left[\frac{K_p^2\,R_2}{R_2^2 + X_{sc}''^2} - j\,\frac{R_2^2 + X_{sc}''\,(X_m + X_2)}{(X_{sc}''^2 + R_2^2)\;(X_m + X_1)}\right] \tag{10}$$

At first sight it may not appear that the right members of (10) and (7) are identical; noting, however, that

$$X_{sc}'' + K_p\,X_m = X_m + X_2$$

Equation (7) becomes

$$\check{I}_{mo} + \check{I}_2\,K_p = E\left[\frac{K_p^2\,R_2}{R_2^2 + X_{sc}''^2} - j\,\frac{R_2^2 + X_{sc}''\,(X_m + X_2)}{(X_{sc}''^2 + R_2^2)\;(X_m + X_1)}\right]$$

Thus the truth of the relation expressed by Equation (1) is demonstrated.

J. F. H. Douglas: I wish to offer my tribute to the excellent paper and point out that I think charts similar to Figs. 16 and 17 could probably be derived and used with great advantage for other types of motors. Of course the analytical method of obtaining these figures would have to be adjusted to suit the circuit of the motor in question.

In deriving these curves a certain simplification in the "exact equivalent circuit" is made. In particular, the no load resistance r_o is transferred to a point nearer the source of supply than the stator reactance.

Inasmuch as stator slots have reactance in proportion to their depth, and in view of the fact that occasionally we run across circle diagrams that are skewed in an opposite sense which regarding the stator resistance only would give, I think that perhaps in some cases the core losses are sufficiently large taken in conjunction with the stator reactance to warrant further consideration of this problem.

The charts were computed on the basis of the assumption of a constancy of core loss. Without attempting to criticize this statement from the practical point of view, I wish to say that there are some theoretical elements involved that are of great importance. I do not recall having seen in print the intimate connection between hysteresis torque and the friction loss of an induction motor. If hysteresis torque is less than friction torque, the losses represented by R_o should decrease with speed but it should be possible to raise the voltage on the stator to such a point that at no load the motor would run in exact synchronism.

The constancy of core loss is also greatly affected by the ratio in which the reactance is split between stator and rotor windings.

It is to be hoped that some of these theoretical points may soon be clarified.

H. Weichsel: (communicated after adjournment) Mr. Branson presents a method which he claims gives accurate results in a minimum time. He compares his with the graphical and analytical methods. The comparison between Mr. Branson's and the analytic method has been carried to a large degree of accuracy. All three methods are based on the assumption that the self-induction coefficient or leakage coefficient is constant and is independent of the current draw of the machine.

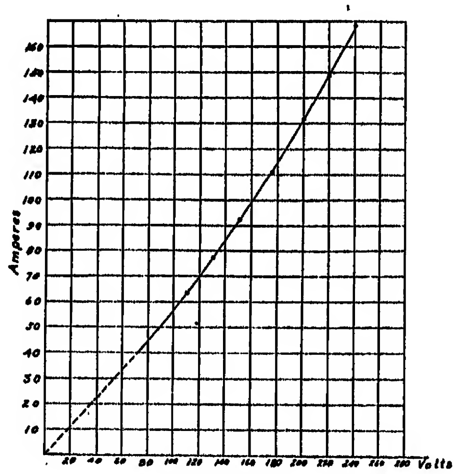


Fig. 4

In practical machines, however, this coefficient is far from constant, and due to the variation of this coefficient any one of the methods will give values which are only approximately correct when compared with tested values.

Fig. 4 herewith shows the short-circuiting current of an 8-pole, 10-hp., 220-volt, 60-cycle motor. It will be noticed that up to about 80 volts the current draw appears proportional to the voltage. In other words the self-induction coefficient up to this voltage is approximately constant. At values above this voltage, the current increases rapidly with increasing voltage, indicating that the self-induction coefficient decreased with increasing voltage.

As Mr. Branson points out, the graphical and analytical ways must give the same results, because they are both based on the same assumption, which means the two methods lead to a current locus which is a circle, a well-known condition derived years ago by Heyland, Behrend, and Osana.

Fig. 5 shows the current locus of the same motor for which the short-circuiting current is given in Fig. 4. It will be noticed that this locus, Fig. 5, is anything but a circle. No. 1 is the locked point of the machine, and No. 2 is the point of idle running. If it is attempted to draw a circle through these points, it is evident it would deviate materially from the curve 1–2. A fairly close approximation can be obtained, however, if as locked point

a current value is used obtained at about half voltage and then multiplied by 2; in other words, if the self-induction coefficient is used which exists at about half voltage. It will be seen that even under these conditions, the results obtained from the tests and those obtained from the circle are only in fair agreement and sufficiently accurate for most practical purposes. The curves referred to above have been based on a machine which has, like most modern machines, totally closed rotor slots. The variation of the self-induction coefficient will not be quite as large in machines having semi-closed slots in the rotor and stator, and also the variation is decreased with decreased number of poles.

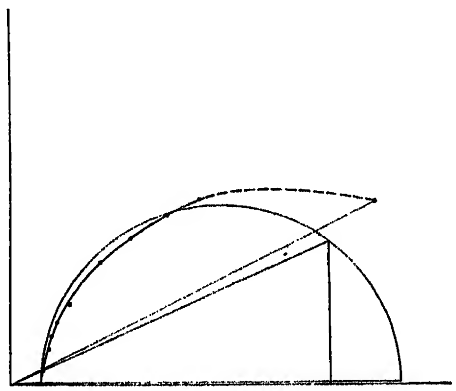


Fig. 5

Nevertheless, the fact remains that in the majority of cases the self-induction coefficient is not constant, and at the best only a reasonable agreement between test and calculated data can be expected as long as the constant self-induction coefficient is used as a basis.

Mr. Branson's method is based on the diagram shown in Fig. 14. This is in principle a circle diagram for an ideal motor having primary and secondary reactance and secondary resistance but no primary resistance. A constant voltage is supposed to be impressed across its terminals. The omission of the primary resistance is corrected by external resistance in each of the three lines in series with the motor. Consequently the line voltage across these three resistances is not constant, but is a function of the current. For historical reasons it may be pointed out that this method of considering the influence of the primary resistance was published in Heubach's book, p. 83, published 1903; and in the book by De La Tour entitled "The Induction Motor," p. 147, published 1903.

The method proposed by Mr. Branson makes the assumption that the primary leakage coefficient is equal to the secondary leakage coefficient, or using the terms preferred by Mr. Branson, the permeance values P_L' and P_L'' are alike. This assumption is more or less correct if the rotor is of the wire-wound type. If it is of the squirrel-cage type, a larger percentage of the leakage exists in the stator than in the rotor.

Heubach also pointed out in his book that for any ratio between stator and rotor leakage, the exact rotor current can be obtained by drawing a diagram as shown in Fig. 6 herewith, where a small circle drawn over the magnetizing current divides this current in the relation of stator leakage to total leakage. The rotor current is vector 1–2 and the stator current vector 0–2 when both are measured with the same scale. If all the leakage is in the stator member, this small circle has a diameter equal to the magnetizing current. As the percentage of the rotor leakage becomes larger and larger, this circle shrinks and finally becomes merely a point located at the end of the magnetizing current vector.

With this diagram as a basis, and to it added the method for considering the primary resistance proposed by Heubach (which is identical to that proposed by De La Tour), a diagram of sufficient accuracy for practical purposes can be obtained. Naturally it has the same shortcoming which was pointed out in the beginning,—it is based on a constant self-induction coefficient. But if desired it can readily be modified to take care of a variable self-induction coefficient by drawing a family of circles for different self-induction coefficients. It is true that this idea can also be followed by any of the methods outlined above. It is more or less a matter of personal preference as to which method is to be used. My opinion is that the graphical method is applicable to any case which may occur and has the advantage that the calculation can be carried out without reference to tables or graphs, which are not always available when calculations are to be made on motors. It further has the advantage that it enables one to visualize the influence of changes in relations of a given design.

In large motors the use of the methods referred to above is rarely justified, because the stator copper loss represents only a small percentage of the total machine input, and in such cases the influence of the ohmic resistance is so small that the simple Heyland diagram is preferred. Generally only in small 60-cycle motors or in medium size low-frequency motors is the stator copper loss a large percentage of the motor input. In such cases any of the above methods can be used to advantage.

W. J. Branson: In the discussion of Mr. Boothby, I am not sure that I got all the points. In regard to the use of K_p in Fig. 12 to show the relation between the secondary current and the increase of the primary current due to the demagnetizing action of the secondary, I might say that the mathematical derivation was given in my 1912 paper to which reference has been made and it is also given in the 1923 edition of Mr. Behrend's book. The two demonstrations are entirely different but the result is the same. With any current flowing in the secondary the amount of increased current in the primary that will flow due to the demagnetizing effect of the secondary is equal to the secondary current times K_p. That is the exact relation so far as the mathematics is concerned. I did not clearly understand whether Mr. Boothby took exception to that or not.

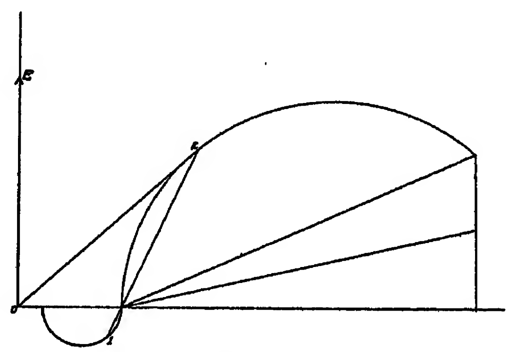


Fig. 6

In reference to Mr. Dudley's statement that it has taken several years to produce a set of *a b* and *a c* curves, it may be well to explain that what has taken the time has not been the actual work of calculating and plotting the curves. The big job was to find a simple and practical way of deriving the values. The first set of curves covering a small range of constants was made by the graphical process about 1910 or 11; and two or three years later a larger set was made in the same way. This method of procedure was very laborious.

The last set of curves, which was made three or four years ago, was plotted from values calculated by the work sheet shown as

Fig. 23. This process requires probably not more than 10 per cent of the labor that would be involved in deriving the values graphically.

Anyone who may wish to try the system before the curves are published can easily make up a small set which will take care of practically all 60 cycle 4-, 6-, and 8-pole motors. Such a set should cover the constants listed below:

K_r 0.94, 0.93, 0.92, 0.91, 0.90, 0.89

r_1/X 0.15, 0.2, 0.25, 0.3, 0.35

It would include five groups of *a b* curves and six groups of *a c* curves, and cover 32 sheets of cross-section paper. A young man who is quick with the slide rule might do all the work in two or three weeks.

Professor Douglas has called attention to the fact that "charts" like Figs. 16 and 17 might be used to advantage for other types of motors. In this connection, I might say that several such "charts" are in regular use. One set of curves has been used for about 15 years to determine the starting torque of split-phase motors while another set has been in use for 6 or 7 years to determine the maximum torque of any single-phase induction motor. In either case the torque values, calculated with the aid of the curves in less than 30 seconds, are exactly the same that would be obtained by constructing a circle diagram in accordance with the directions given in my 1912 paper.

Mr. Weichsel has called attention to the fact that the variation of the leakage coefficient, which corresponds to a decrease in reactance as the load comes on, will cause the actual performance to differ from the calculated performance regardless of the theoretical accuracy with which calculations are made. In the case of motors with closed rotor slots, it is undoubtedly true that the reactance sometimes varies over such a wide range as to interfere seriously with any simple mathematical treatment. For motors with semi-enclosed or open slots on the other hand, my observation has been that the variation of reactance is seldom great enough to have an appreciable effect on the practical value of the calculations.

A Recording Torque Indicator

That Records the Torsional Effort of Motors During Acceleration

BY G. R. ANDERSON[1]
Member, A. I. E. E.

Synopsis.—*The measurement of torque under unstable conditions of speed is usually extremely difficult and inaccurate when a dynamometer, prony brake, or similar torque measuring equipment is used. The device described in this paper was developed primarily to obtain torque measurements under unstable conditions as well as under stable conditions, and to obtain a permanent record of these measurements. It has been particularly successful in recording speed-torque curves of motors during acceleration and it can also be applied very effectively to other fields.*

* * * * *

Introduction

It is a relatively simple matter to measure, with a fair degree of accuracy, the speed and torque of an induction motor for any load between no-load and the pull-out point of the motor if the speed is steady. The static torque of the motor is also easily measured, but between these points where the speed is usually unstable, it is much more difficult to obtain satisfactory measurement. With the development of line-start motors, condenser motors, etc., it is becoming increasingly more important to know exactly the torque characteristics that the motor will develop. Dips in torque due to harmonics or other causes may be present in sufficient magnitude to seriously hinder the motor in accelerating its load. A device that will quickly and accurately record this torque should therefore find many uses in analyzing and improving motor characteristics. Such a device is described in this paper.

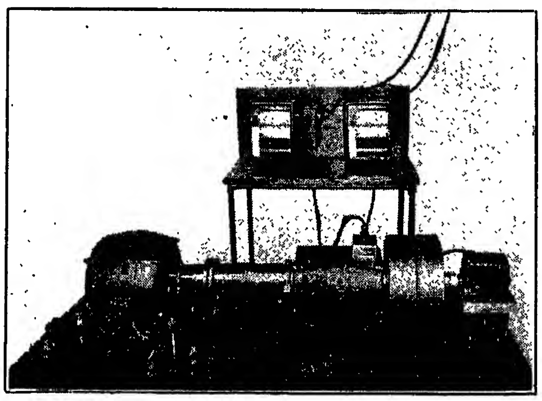


Fig. 1—Torque Indicator Set-up for Measuring Starting Torque of Induction Motor

Description of Torsional Indicator

Fig. 1 illustrates the torsional indicator set up to take speed and torque curves on a squirrel-cage induction motor. The device consists of (1) a helical spring capable of transmitting the torque of the motor and giving an angular deflection proportional to the torque, and (2) an electromagnetic circuit of two elements that are displaced from each other by an angle equal to the deflection of the spring. A recording electrically-operated position finder is connected to the device to record the amount of angular deflection, which is proportional to the torque.

The helical torsion spring is accurately finished and is mounted so as to eliminate any distortion due to centrifugal forces. The spring is equipped with a damping sleeve that prevents fluctuations due to the natural period of vibration of the spring and elements, from being recorded on the chart. Full-scale deflection on the meter is obtained with a spring deflection of 60 degrees. Several sizes of springs can be interchangeably mounted to take care of various ranges of torque.

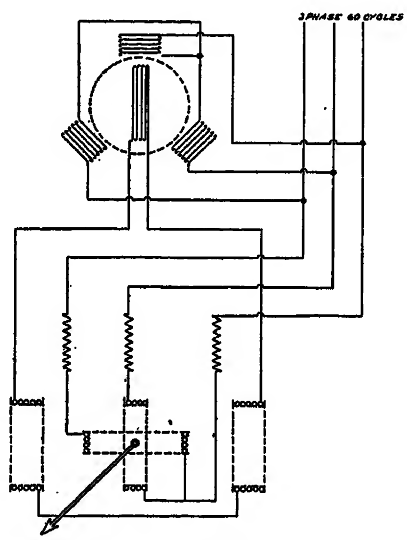


Fig. 2—Circuit Diagram of Torque Indicator

The electromagnetic elements are mounted on two concentric cores, one of which revolves with the motor and the other with the load. The first element consists of a three-phase winding arranged symmetrically outside of the second element. This is shown diagrammatically in Fig. 2. This three-phase winding is

1. Development Engineer, Fairbanks, Morse & Co., Beloit, Wisconsin.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

excited through slip-rings from an external three-phase source of power. The second element contains a winding which is connected by another set of slip rings to the position finder as shown. The moving coils of the position finder are connected to the external source of power. When the first element is turned with respect to the second, the phase angle of the voltage generated in the second, is changed and this causes a deflection of the position indicator proportional to the torque. A tachometer generator and recording meter are used to measure the speed. The charts for recording both the torque and the speed are mounted on the same shaft in order to provide synchronized readings. Gear combinations in the tachometer generator allow different full-scale values of speed on the chart. It is obvious that the meter circuit can be so designed that the needle deflection is closely proportional to the angular deflection in the electromagnetic circuit of the device, thereby allowing the use of standard chart paper.

The device is similar in action to a d-c. meter in that it records average values and is well damped. It will not record very rapid fluctuations of torque but it does produce fairly accurate quantitative measurements.

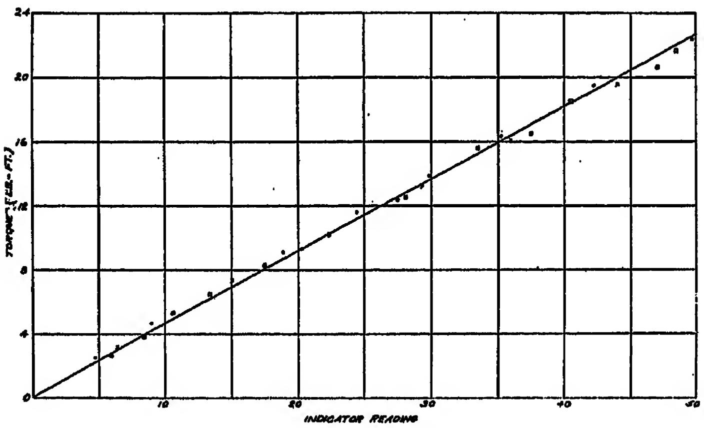


Fig. 3—Calibration Curve of Torque Indicator

. —1800 Rev. per min.
x —1200 Rev. per min.
0 — 600 Rev. per min.
□ — 0 Rev. per min.

Calibration

Calibration of the device is accomplished by placing it between a dynamometer and a load and recording the torque output of the dynamometer and the instrument reading. Fig. 3 is a calibration curve for a given spring showing the relation between actual torque and instrument reading. The plotted readings were taken over a wide range of speed and of torque and clearly indicate that centrifugal force has no serious influence on the accuracy of the device. While the calibration curve is actually slightly S-shaped, for practical purposes it may be considered a straight line, since the error introduced by such assumption is extremely small.

Methods of Loading

Since this device indicates transmitted torque and speed simultaneously and records these values on a chart, it is obvious that any suitable method of loading can be applied. In the case of taking speed and torque curves on motors during acceleration it has been found that a simple flywheel load is most satisfactory. Under these conditions, the entire torque output of the motor is utilized to accelerate an inertia load, neglecting friction, and the rate of acceleration is proportional to the torque transmitted at that speed. The rate of acceleration can be readily determined from the speed-time chart. The torque indicated on the chart is the torque transmitted through the spring, and is equal to the torque developed by the motor less that required to accelerate its rotor. Thus the indicated torque during acceleration will be slightly less than that shown at stable speeds and will be proportional at all speeds to the ratio of the WR^2 of the flywheel and device to the WR^2 of the entire rotating mass. By calculating the WR^2 of the rotor and determining the rate of acceleration from the chart, the ratio of developed torque to transmitted torque can be found. It is obvious that this ratio will hold constant for all conditions of acceleration of a simple flywheel load.

In practise the torque available for bringing a load up to speed is the developed torque less that necessary to accelerate the rotor so that the indicated torque as produced on the chart actually represents the torque available at the shaft for the accelerating period as shown. In general it will be found that when the accelerating period exceeds 15 or 20 sec., the difference between the developed torque and transmitted torque will be less than four or five per cent. The necessary time to allow for full acceleration of a motor should not be less than 10 or 15 sec. in order that the pen of the instrument may follow accurately the changes of torque. It has been noted also that accelerating periods of 20 to 30 sec. usually cause such a small change in motor temperature that this factor can be neglected.

In the following examples the instrument chart speed was 12 in. per min., each cross-division representing a time of 3.75 sec.

Applications

Fig. 4 is an example of speed and torque charts taken on a 5-hp., 1800-rev. per min., 60-cycle, repulsion-induction motor. The variations in torque at start due to the commutator are clearly shown as well as the point of operation of the short-circuiting device and change over from repulsion to induction torques. Charts of this kind were taken to show the effect of setting the short-circuiting device to operate at different speeds.

Other charts taken on repulsion-induction motors, clearly show the change in shape of the repulsion torque curve due to change in brush setting and the lowering

of pull-in torque when the brushes are displaced from neutral by more than the proper angle.

Fig. 5 shows records taken on a line-start squirrel-cage induction motor. In addition to the charts of torque and speed, synchronized charts that recorded the current and power input were also obtained with a constant voltage applied to the terminals of the motor. Several of these motors with different types of rotor construction were tested in order that an accurate comparison of the characteristics of each type might be obtained.

It was noted from the charts that each of these motors having a rotor winding of special shape designed to lower the current drawn by the motor from the line

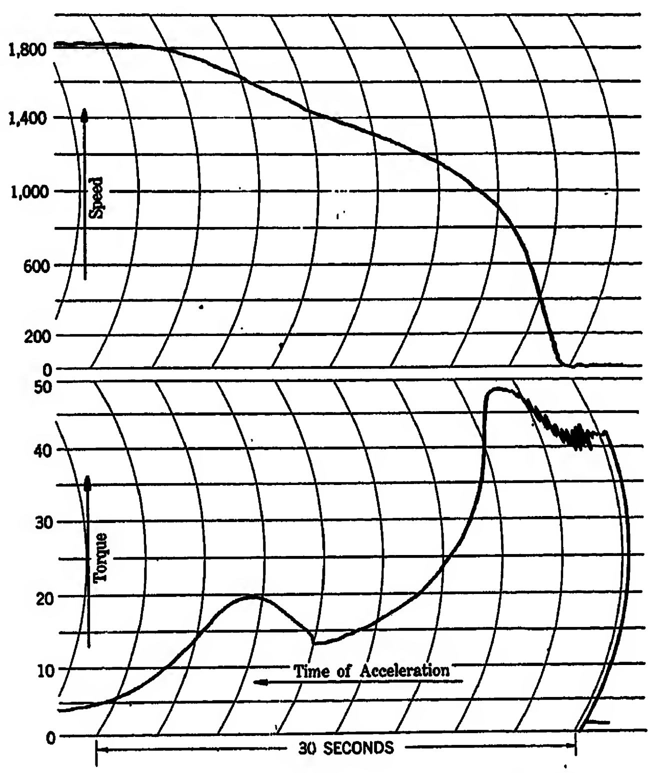


FIG. 4—SPEED AND TORQUE CURVES OF REPULSION-INDUCTION MOTOR DURING STARTING

This is a 5-hp. 1800-rev. per min. 60-cycle, 220-volt single-phase motor

during starting, had an appreciable dip in accelerating torque. The knowledge thus obtained of the exact amount of accelerating torque at all speeds should prevent misapplications of these motors.

By means of the addition of current and wattmeter readings, the factors affecting the developed torque of the motor can be determined from tests for all speeds. The change in rotor resistance and reactance with changes in slip can be calculated and the value of any particular type of rotor construction for a given condition can thereby be determined.

In making tests on squirrel-cage induction motors it was found that invariably the indicator recorded distinct torque pulsations whenever the motor became noisy. Investigation with this device also verified the general belief that dips in torque due to harmonics in squirrel-cage motors are more pronounced at low

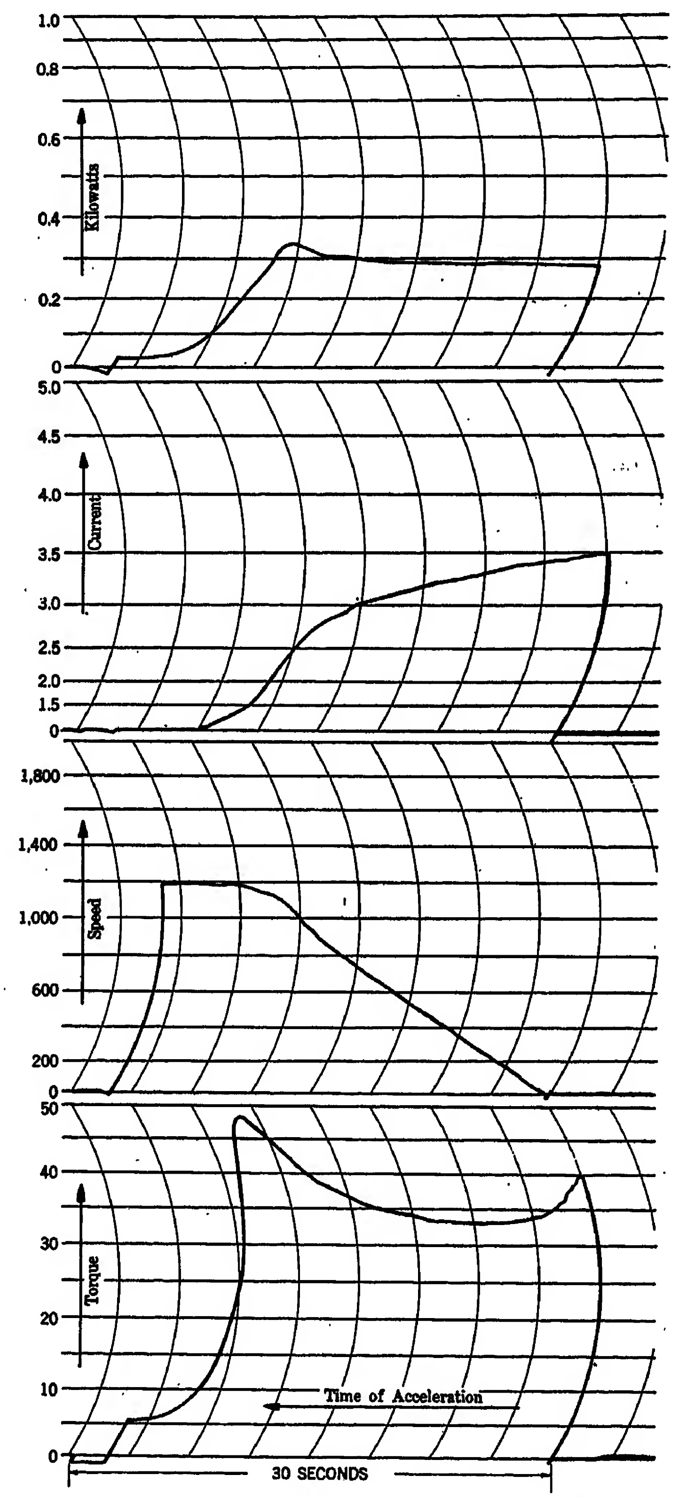


FIG. 5—RECORDS TAKEN DURING ACCELERATION OF A LINE-START INDUCTION MOTOR

Curves are shown for kw., amperes, speed, and torque of a 20-hp. 1200-rev. per min. three-phase 60-cycle motor

voltage than at high voltage. A series of curves taken on a motor with different values of voltage applied to the terminals showed a damping out of harmonics as

the voltage was increased. It seems reasonable therefore to assume that if a motor develops a satisfactory speed-torque characteristic on reduced voltage, it will show an equally satisfactory characteristic at any higher voltage.

The charts shown here illustrate the speed and torque characteristics of motors of various types. It is quite apparent, however, that a recording torsional indicator can be used to advantage also in many other fields of investigation. For example, its operation can be reversed and in place of recording the torque output of a motor it could record the torque necessary to start and run a given load. By so doing definite data could be obtained as to the load and the most economical type and size of motor could be applied.

ACKNOWLEDGEMENT

The writer wishes to acknowledge the valuable assistance given by Mr. D. J. Angus of the Esterline Angus Company in developing the meter for this device.

Discussion

B. F. Bailey: Any one who has attempted to determine the speed-torque curves of induction motors is well aware of the difficulties involved due to instability and to rapid heating of the rotor. In the method discussed the entire operation takes only a short time so that the heating effect is negligible and any difficulty due to instability is obviated since the readings are taken while the motor is accelerating. It appears that the method should be rather simple to apply and that the results should be valuable as indicating the ability of the motor to start its load.

For more exact work the method is open to some objection. If the acceleration is rapid a considerable proportion of the torque developed is used in accelerating the rotor and this part does not appear upon the record. It is moreover quite obvious that the needle of the curve-tracing instrument is incapable of following very rapid variations and consequently the curve may be smoothed out to a considerable extent. In order that the curve should show all the variations it would appear to be necessary to make use of the oscillograph or some similar device. Such a method will obviously not be so readily applicable to workshop conditions but should be capable of following all the variations of the speed-torque curve. Some work with which the writer is familiar seems to indicate that there are some surprising variations which no one has apparently previously considered possible.

G. W. Penney: The method of measuring torque by means of the torsion dynamometer is quite convenient in most cases and the method of indicating the deflection of the spring which is described in this paper is very interesting. However, I believe that this device has a serious limitation in that a large angular deflection of the spring is required, for, as stated by the author, 60 deg. deflection is required to give a full scale reading. In other words if we wish to measure the starting torque of a motor, actually the motor has moved through 60 deg. before a full scale reading can be obtained. In the same way, if the torque suddenly changes this change cannot be indicated until the spring has deflected.

This helical spring between the motor and the load gives a natural period of oscillation between the two rotors which is inherently low so that the damping device becomes of considerable importance. An ordinary friction device having sufficient friction to prevent oscillations of the rotor would tend to restrict the deflection of the spring, giving a reading which is too low in case the torque is increasing and too high if decreasing. The details of the damping device used would, therefore, be interesting and especially test results showing whether the calibration is the same for both increasing and decreasing torque.

This principle of using the deflection of a spring as a measure of torque transmitted has frequently been used and devices described in the literature for measuring the torsional deflection. I believe that one of the best of these devices is the "Moulin Torsion Meter."[1] In this torsion meter the deflection of the spring was measured by measuring the change in impedance of two coils as the air-gap between the cores changes. In this way very small movements can be measured so that the spring of the dynamometer can be very stiff. Several modifications of this magnetic device have been described in the literature recently[2,3] which reduce the size of this instrument and increase its sensitivity to a point where ordinary shafting can be used as the dynamometer spring. At the Westinghouse works a few years ago, we used one of these devices which was sensitive to $\frac{1}{100{,}000}$ in. One-half thousandth of an inch movement gave a change in deflection of 2 in. on the oscillogram. This device was used for measuring short-circuit torque and was satisfactory up to 120 or 200 cycles torque frequency.

As the author states, it is relatively easy to measure torque during steady conditions by loading a motor against a d-c. generator. An accelerating time of 30 sec. would come almost within the range of this method if recording meters are used. If the author was interested only in an accelerating time of 10 to 30 sec. the instrument described would be satisfactory if properly damped. However, I hardly see the need of building a special device which is limited only to this range when the Moulin type of torsion meter with later modifications can measure an almost unlimited range of accelerations. Also, I believe it is more simple for the following reasons:

1. Fewer slip rings are required.
2. For ordinary rates of acceleration no damping is required since the spring is merely a portion of the regular shaft which gives a natural frequency well above ordinary pulsations in torque.
3. A special recording meter would not need to be developed. For slower rates of acceleration a standard recording meter would be used with 60-cycle exciting current for the electric micrometer. For higher rates of acceleration the oscillograph would be used for recording. For torque pulsations above 15 cycles frequency, 500-cycle exciting current would be used. Such a torque meter would therefore have an almost unlimited range and would require only standard recording devices.

G. R. Anderson: Professor Bailey is perfectly correct in that the instrument is simply a commercial piece of apparatus convenient for production testing. I should certainly like to see a torque meter with such a small inertia in its moving elements that it could follow any minute variation such as an oscillograph does in recording electrical units.

In regard to the damping device that was on the spring, it was a friction device, but no friction was applied to the spring unless the torque was actually reversed. In other words, as long as there was positive torque transmitted by the spring there was no damping.

I think that this will answer Mr. Penney's criticism of the inaccuracy that might be caused due to damping. If the torque happened to go to a negative direction damping would occur and the inaccuracy would be there, but no readings would be obtained.

1. *Engineering*, June 13, 1924, p. 764.
2. *Vibration Recorder*, by A. V. Mershon, A. I. E. E. TRANS., Vol. XLV, 1926, p. 1007.
3. *An Instrument for Measuring Short-Circuit Torque*, by G. W. Penney, A. I. E. E. JOURNAL, Nov. 1926, p. 1151.

Several different kinds of damping means were considered. We were interested mainly in one thing, and that was eliminating the natural period of oscillation that might be set up in the spring.

Engine builders have for a great many years studied the problem of measuring torque and torque vibrations. A number of different devices has been used for recording of Diesel engine torque variations and it has been the experience of the company with which I am connected that none has been entirely satisfactory. There are certain features about such measuring devices similar to the Moulin Torsionmeter described by Mr. Penney, that may work out in the laboratory but are unsuitable for commercial work. However, I do know that we did not consider them for the measurement of torque of motors, simply because we wanted a fairly reliable commercial piece of apparatus by which we could test all kinds of motors and use a standard recording instrument. If the measurement of torque under unstable conditions of speed is so easily obtained, I cannot understand why it is that authors in the past have drawn such smooth curves for line-start motors in which there were no depressions in torque between starting and maximum.

Stability of Synchronous Machines

Effect of Armature Circuit Resistance

BY C. A. NICKLE*
Associate, A. I. E. E.

and

C. A. PIERCE*
Non-member

Synopsis.—The theory of synchronous machines as developed by Doherty and Nickle[1] has been extended to include a determination of the effect of armature circuit resistance on damping torque. Equations are developed for the damping torque of synchronous machines in general, i. e., both the salient-pole and round rotor types. These equations assume an exciting winding in the direct axis and an amortisseur winding in the quadrature axis, and further assume that all damping is due to currents induced in these two windings. The effect of an amortisseur winding in the direct axis is not considered because its damping action at the low frequency of hunting is small compared to that of the exciting winding. It is shown that the damping torque of any synchronous machine can become negative, giving instability, if the armature resistance is increased beyond a critical limiting value. This fact has been known,[2] but an actual determination of the value of the critical resistance in terms of constants of the machine has not, to the authors' knowledge, been available. This value, for a salient-pole generator with normal excitation and no amortisseur winding, is

$$r = x_q \tan \delta'$$

where r is armature circuit resistance†, x_q is quadrature synchronous reactance, and δ' is the steady-state displacement angle. If r is less than the critical limiting value, the damping torque is positive; if greater, negative.

The damping of a generator increases in the positive direction with increase in load. Thus a salient-pole generator with amortisseur winding, if stable at no load, will be stable under any steady load within its steady-state power limit. With $\delta' = 0$, and normal excitation, the critical limiting value of armature resistance for a machine with an amortisseur winding is

$$r = \sqrt{b\,d + \frac{d}{b}\,(x_d - a)^2}$$

where x_d is the direct synchronous reactance and a, b, d are constants depending upon the design of the machine. This formula is useful for determining the constants of an amortisseur winding which would prevent sustained or cumulative oscillations of a generator.

The analysis also shows that a round-rotor generator with identical field windings in the direct and quadrature axes may be made unstable by too much resistance in the armature circuits. This fact had been previously established by Dreyfus.[2]

The relations for inherent stability in synchronous motors are not so simple as for generators, but definite relations involving armature resistance will be found in the article.

The mathematical analysis is checked with laboratory experiments.

INTRODUCTION

THE problem of sustained and cumulative oscillations due to an impressed periodic exciting torque has been fully treated in the literature of synchronous machines.[3] It is further known, as shown by Dr. Ludwig Dreyfus,[2] that sustained and cumulative oscillations can occur without the presence of a periodic exciting torque. He called these oscillations self excited, because they can be started by an impulse of momentary duration; and once started become self sustaining, provided conditions favorable to such oscillations exist in the circuits of the machine.

His method of attack was to set up and solve the differential equations for the magnetic fields of a round-rotor machine under the conditions of small forced oscillations. The final equations of this analysis are based on a round-rotor machine with a damping winding in the quadrature axis having the same constants as the d-c. field winding. He showed by means of these equations that self-excited oscillations may be set up, i. e., that negative damping is possible. He showed, furthermore, that the conditions favorable for negative damping are high excitation, low line frequency, and a large value of armature resistance. In the conclusion to the paper, it is stated that the oscillations of the exciting current due to transformer action between armature and field help to stabilize the machine, and a well-designed amortisseur winding in the quadrature axis will completely suppress the self-excited oscillations.

While Dr. Dreyfus initially considers both salient-pole and round-rotor machines in his paper, the part of the mathematical analysis dealing with self-excited oscillations in an actual machine is based on a machine with a uniform air gap. It is desirable to extend the analysis to include salient-pole machines. The necessity for considering this type is proved by engineering experience. Certain instances of troublesome hunting with salient-pole generators have come to notice from time to time that were difficult to explain. It was believed that too large armature resistance was to blame, but no analysis of the effect of this resistance was available with which to check the belief. This paper is the direct outcome of this problem. It takes up the mathematical analysis and solution for the effect of armature circuit resistance on damping torque of the salient-pole machine, and includes experimental verification of the mathematical solution, as well as application of the conclusion to a practical problem.

The mathematical analysis is based on the vector

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†Armature circuit resistance includes the resistance of armature phase and line wire back to the system bus. Likewise, synchronous reactance includes the reactance of line wire as well as the synchronous reactance of the phase. These quantities will usually be referred to as armature resistance and synchronous reactance.

1. For references see Bibliography.

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diagram rather than on the original differential equations for the machine, and is an extension of an Institute paper[1b] on torque-angle characteristics of synchronous machines under transient conditions. In the paper just referred to, equations for both synchronizing and damping torque were developed for salient-pole machines based on the assumption of zero armature circuit resistance. This assumption, in so far as it affects torque angle characteristics, had been justified in an earlier Institute paper[1a] by the same authors. The mathematical analysis will now be extended to show the effect of armature circuit resistance on damping torque.

In the mathematical analysis, the synchronous machine is considered to have a main-field winding in the direct axis and a damping winding in the quadrature axis. Although the ordinary amortisseur winding gives damping in both axes, its effect in the direct axis is neglected, since at the low frequency of oscillation usually encountered, the damping of the main-field winding predominates. This method of attack gives a solution that can be readily simplified to apply when there is no amortisseur winding. Since a great many machines have no amortisseur winding, this case has been considered in some detail.

Damping due to means other than the main-field winding and the amortisseur winding is not considered. Any external damping that may exist can be added to the inherent damping of the two windings if it is desired to determine the total damping acting on the rotor.

Saturation of the magnetic circuits is not considered. To include the effects of saturation would unduly complicate the mathematical analysis, if it did not make a solution impossible.

Assumptions

In order to simplify the mathematical work, certain assumptions are made which do not seriously impair the usefulness of the conclusions derived. The assumptions are:

1. The machine is assumed to be connected to a relatively large power system so that hunting of the machine will cause no appreciable variation in the bus voltage; *i. e.*, an infinite bus is assumed.

2. The polyphase voltages impressed on the armature circuits of the machine and the currents flowing therein are assumed to be balanced and to vary sinusoidally with respect to time. Thus the usual vector diagram for voltage and current per phase may be used to represent the steady-value voltages and currents of the machine.

3. The machine is assumed to be in a state of sustained oscillation about a constant average value of displacement angle. The electromagnetic torque is then a function of time and contains two components, *viz.*, one component in time phase with the angular velocity of oscillation, and the other in phase with the angular displacement. These components are the damping torque and the synchronizing torque, respectively. The assumption is further made that the differential equations at the point considered are linear. Thus this analysis of damping applies rigorously only when the oscillations are of very small amplitude, *i. e.*, when voltage, current, torque, etc., vary proportionately. The motion of the rotor is assumed to consist, then, of a steady rotation at synchronous speed upon which is superimposed a sinusoidal oscillatory, or alternating motion.

4. The angular velocity of oscillation is assumed to be very small compared with the steady-value angular velocity; hence torque and power may be assumed numerically equal in the per-unit system.[4]

5. The alternating component of motion of the rotor causes the amplitude of the polyphase currents to vary periodically in time at the frequency of oscillation. It is assumed that the peak value of the armature current pulsates, or is modulated, in such manner that the envelope of the peak values can be represented as a sinusoidal function with respect to time, having a period equal to the period of hunting. If the actual modulation is more complex than assumed, the analysis will hold in so far as the fundamental of the modulation is concerned.

Preliminary Analysis

An outline of the reactions produced by the modulated polyphase armature currents is set down in order that the mathematical analysis may be more easily followed. The currents in the several phases produce the armature reaction, or armature m. m. f., which can be resolved under steady-state conditions into space fundamental and space harmonic components.[1a] Only the space fundamental component will be considered.

The steady-value space fundamental component of armature reaction revolves around the air gap synchronously with the field poles, and cannot induce current in either of the two field windings. But the modulated armature reaction does induce current by transformer action in each of the rotor windings. The current in the main field winding, *i. e.*, in the direct axis, is made up of two components. One component is the steady-value current which is set up by the exciter; and the second component is alternating current induced by the modulated armature reaction. Only alternating current flows in the quadrature winding. The frequency of the currents induced in both windings is the same as the frequency of hunting of the machine. Thus the modulation of the peak value of the armature current produces a modulation of the total rotor voltage, *i. e.*, of the nominal voltage of the armature winding.

As the permeance of the air gap of a salient-pole machine is different in the two axes, in order to make the analysis perfectly general, it is necessary to deal with the direct and quadrature components of voltage and current.[1a] It is evident that these components of the armature current will be modulated if the total current is modulated, and that the modulation will

appear in the direct and quadrature components of the nominal voltage by transformer action.

Since the modulation of the steady peak value i_d' of the direct component of armature current causes its amplitude to vary sinusoidally at the frequency of hunting, the peak value i_d at any instant is a function of time and can be represented as

$$i_d = i_d' + \Delta\, i_d \cos s\, t = i_d' + [\Delta\, i_d] \tag{1}$$

where s is the angular velocity of modulation expressed as a fraction of normal angular velocity, and $[\Delta\, i_d] = \Delta\, i_d \cos s\, t$ is the value of the modulating wave at any instant. Using the per-unit system of units,

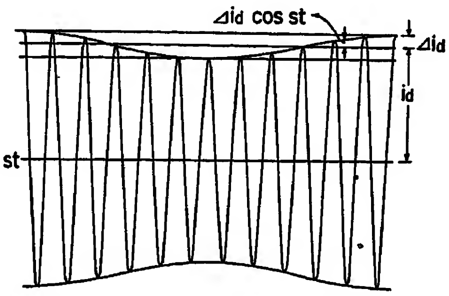

FIG. 1—ARMATURE CURRENT WITH HARMONIC MODULATION

frequency and its corresponding angular velocity are numerically equal. Fig. 1 shows the current represented by Equation (1). It will be assumed that the angular velocity s is small compared with ω, the angular velocity corresponding to line frequency, so that the modulation will not distort the wave form of the current during a cycle enough to make the use of the usual vector representation of polyphase currents inaccurate.

In like manner the peak value i_q of the quadrature component of armature current is a function of time and can be represented as

$$i_q = i_q' + \Delta\, i_q \cos (s\, t + \alpha) = i_q' + [\Delta\, i_q] \tag{2}$$

introducing the time-phase angle α because the modulating waves for the direct and quadrature components of current will not in general vary in time phase with each other. In Equation (2) i_q' is the average value of i_q and $[\Delta\, i_q] = \Delta\, i_q \cos (s\, t + \alpha)$ is the value of the modulating wave.

The peak value of the nominal voltage, e_d, due to the main field winding, is a function of time and can be represented as

$$e_d = e_d' + [\Delta\, e_d] \tag{3}$$

where e_d' is the average peak value and $[\Delta\, e_d]$ is the modulation, or alternating, component introduced by the hunting. As there is no d-c. excitation in the quadrature axis, the peak value of the nominal voltage e_q can be represented as

$$e_q = [\Delta\, e_q] \tag{4}$$

where $[\Delta\, e_q]$ is a function of time.

The displacement angle δ, which is made up of two component angles, the steady value δ' corresponding to the average load, and an alternating value $[\Delta\, \delta]$ corresponding to the hunting, can be represented as

$$\delta = \delta' + [\Delta\, \delta] \tag{5}$$

The alternating components $[\Delta\, i_d]$, $[\Delta\, i_q]$, $[\Delta\, e_d]$, $[\Delta\, e_q]$, and $[\Delta\, \delta]$ all vary in time with the frequency of hunting.

These values of armature current, nominal voltage, and load angle can be combined by means of the relations shown in the vector diagram, Fig. 2, for a salient-pole machine to give relations from which the damping torque can be determined. The mathematical analysis is given in Appendix I. Equation (56) of Appendix I gives the value of damping torque for a synchronous machine having an exciting winding in the direct axis of the rotor and an amortisseur winding in the quadrature axis.

STUDY OF DAMPING TORQUE

It is not immediately apparent from inspection of Equation (56) how much effect armature resistance r has on damping torque T_d, because r appears not only as seen in the equation, but also in the equations for the constants, α, B, C, and D. Equation (56) can be reduced to a simpler form, however, by letting $c = 0 = d$ (compare (26) and (27)), which means considering a machine that has no amortisseur winding,

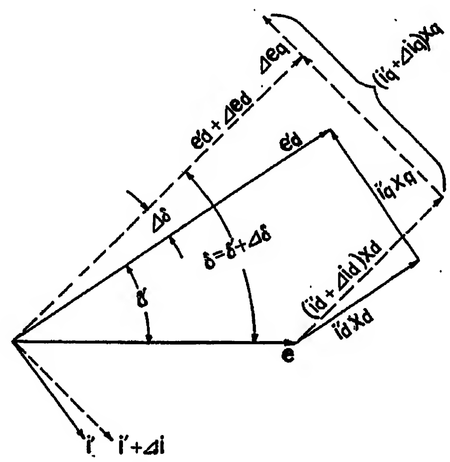

FIG. 2—VECTOR DIAGRAM FOR SALIENT POLE MACHINE ON INFINITE BUS UNDER CONDITIONS OF MECHANICAL OSCILLATION

in which case damping is due to the current induced in the main field winding.

Substituting $c = 0 = d$ in (50), (41), and (56),

$$D = \frac{r \sin \alpha - x_q \tan \delta' \sin \alpha}{b} \tag{58}$$

$$\cos \alpha = \frac{r \tan \delta' + (x_d - a)}{-\, b} \tag{59}$$

$$T_d = \frac{B\, D\, e \sin \delta' \left[D\, b\, x_d + r\, (b \cos \alpha - a \sin \alpha)\right]}{s[(r \sin \alpha - b\, D)^2 + \{r \cos \alpha + D(x_d - a)\}^2]} \tag{60}$$

The damping torque for this case can be written more

simply by substituting (58) and (59) in (60) and reducing; thus obtaining

$$T_d = \frac{B b e\,(r^2 + x_d\,x_q)\,(x_q \tan\delta' - r)\cos\delta'}{s\,[\{b\,x_q\}^2 + \{r^2 + x_q\,(x_d - a)\}^2]} \tag{61}$$

The quantities e, a, b, x_d, x_q, r, s, and $\cos\delta'$ are all positive. Thus the sign of the damping torque is determined by the quantities B and $(x_q \tan\delta' - r)$. Hence Equation (61) for damping torque of a synchronous machine can be rewritten as

$$T_d = K\,B\,(x_q \tan\delta' - r) \tag{62}$$

where K is a positive constant including various constants of the machine.

Inspection of Equation (47) shows that the quantity B can become negative in value with positive values of displacement angle δ' if the nominal voltage e'_d is sufficiently small, *i. e.*, if the excitation is sufficiently reduced. However, under usual conditions of operation as a generator, the quantity B is positive in value. Thus Equation (62) shows that a generator without amortisseur winding will be negatively damped and will oscillate at no load unless stabilized by positive damping external to the main-field winding. The relation that must exist in order for the machine to show inherent positive damping, *i. e.*, damping due to the main field winding, is

$$r < x_q \tan\delta' \tag{63}$$

The critical value of resistance is $r = x_q \tan\delta'$; if the resistance is greater than this value, the inherent damping becomes negative in value.

The case is somewhat different for a synchronous motor. Inspection of Equation (47) shows that the constant B may be positive or negative in value depending on the values of the armature resistance r, displacement angle δ', which is negative for a motor, and the amount of excitation, which determines e_d'. With negative values of δ', the quantity $(x_q \tan\delta' - r)$ is negative in value. Thus for a motor in which all damping is due to current induced in the main field winding, the damping will be positive or negative as determined by the value of B. If B is negative, the damping is positive; if B is positive, the damping is negative. Further inspection of Equation (47) shows that the character of the damping in a motor also depends on the armature resistance r; compare Fig. 6.

The difference between the action of positive and of negative damping should be clearly understood. The action of positive damping tends to reduce the magnitude of the oscillation. Cumulative hunting can occur with positive damping only when the power which sets up the oscillation is greater than the power dissipated as heat. But negative damping acts otherwise. If an oscillation is started, as by a change in load, for instance, it will be cumulative unless the action of the negative damping is neutralized by other sources of positive damping.

Graphical Illustration of Results of Mathematical Analysis

Several curves have been determined by means of the preceding equations to show the effect that armature resistance has on damping torque of a synchronous machine which is connected to an infinite bus and carries a constant load. The machine constants were chosen for illustrative purposes alone, and do not represent an actual machine. The two curves in Fig. 3 show the variation of damping torque for a synchronous generator which has no amortisseur winding, when the armature resistance is varied from zero to 0.75, *i. e.*, to 75 per cent. The values in the per unit system[4] of the constants

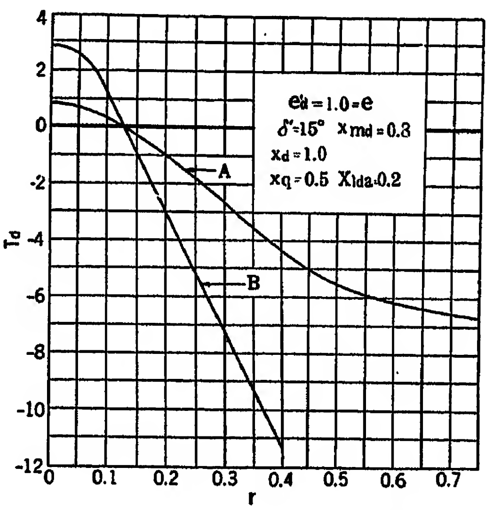

Fig. 3—Curves of Damping Torque as a Function of Armature Resistance—No Damping Winding

(A) Field resistance, R_{da}, in armature terms = 0.05
(B) Field resistance = 0.01

which were used for the curves are $s = 0.02$, $e_d' = 1 = e$, $x_d = 1$, $x_q = 0.5$, $x_{md} = 0.8$, $X_{lda} = 0.2$, $\delta' = 15$ deg. Curve A is for a main field resistance of $R_{da} = 0.05$ and Curve B is for $R_{da} = 0.01$. These curves are computed by means of Equations (61) and (47).

Since the damping for the conditions of Fig. 3 is caused by absorption of power in resistance loss due to current induced in the main field winding, it is to be expected that less resistance in the field circuit will give greater damping, as shown by the two curves. But until Equations (62) and (63) were derived, there had been no way of determining, so far as the authors know, that the damping of a salient-pole machine would become negative in value for an armature resistance greater than a certain critical value which the analysis shows to be $r = x_q \tan\delta'$. The value of main-field resistance is important in determining the amount of damping but does not determine whether it is positive or negative in value; this is determined by the value of the armature resistance.

The critical armature resistance for the constants assumed is $r = 0.134$, which is a much larger value than would be found in the windings of an armature, but is not an unusual value when the line back to the infinite bus is considered. Furthermore, Equation (63) shows that the critical value is increased proportionally to the increase in the tangent of the steady-load displacement angle. Thus a generator may hunt badly on light loads and yet run satisfactorily under larger loads.

The curves in Fig. 4 are based on Equations (56),

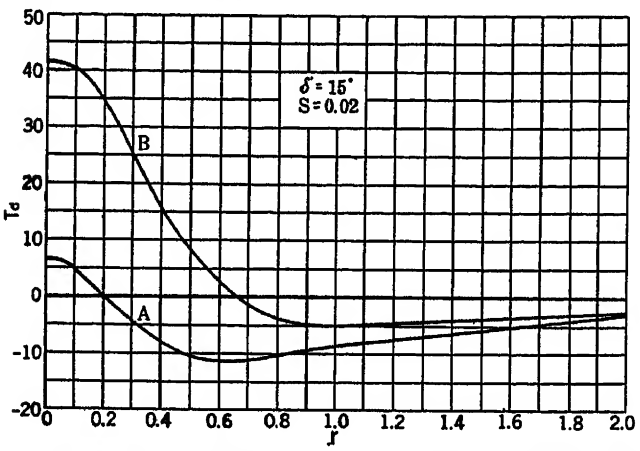

Fig. 4—Same as Curve A of Fig. 3 except with Amortisseur Winding Present

(A) $R_{da} = 0.05$, $R_{qa} = 0.1$, $X_{lqa} = 0.1$
(B) $R_{da} = 0.05 = R_{qa}$ $X_{lqa} = 0.2$

(47), and (48), and show the change in damping brought about by adding an amortisseur winding in the quadrature axis to the generator assumed for Curve A, Fig. 3. The constants of the damping winding for Curve A, Fig. 4, are $R_{qa} = 0.1$, $x_{mq} = 0.3$, and $X_{lqa} = 0.1$. For Curve B the quadrature damping winding is given the same constants as the main field circuit. The effect of the amortisseur winding is seen to be two fold; namely, to increase the amount of positive damping, and to increase the critical value of the armature resistance. But comparison of Fig. 4 with Fig. 3 shows that the general form of the damping torque-armature resistance characteristic has not been changed by the addition of the damping winding. Evidently, any synchronous generator can be made unstable by adding enough resistance to the armature circuits. Compare, Hunting of Round-Rotor Synchronous Machines.

Curve T_d in Fig. 5 was computed for conditions and constants the same as for Curve B, Fig. 4, except that the excitation was removed, the field winding remaining short-circuited through the exciter. This curve is based on Equations (56), (47), and (48). The curve shows that there is no value of armature resistance which will cause hunting. This condition is easily understood, because the generator is operating essentially as an induction machine.

Fig. 6 is based on Equations (61) and (47), and shows the change in the values of damping torque and the constant B when the load, which is a function of δ', is varied from large positive values to zero, the generator range, and from zero to large negative values, the motor range. The five curves are based on armature resistance $r = 0$, $r = 0.05$, $r = 0.1$, $r = 0.2$, and $r = 0.4$. The other constants are the same as in Curve A, Fig. 3. The excitation is held constant at unit value, $e_d' = 1$.

These curves show that the damping torque passes through zero to negative values at $(x_q \tan \delta' - r) = 0$ in the generator range, and passes through zero to positive values when $B = 0$ in the motor range, as the displacement angle changes from large positive values through zero to large negative values. Compare Equation (62) for the relation between damping torque, the constant B, and the displacement angle δ'. Under normal conditions of excitation the constant B is a positive quantity throughout the generator range of load; but passes from positive to negative values somewhere in the motor range of load. So long as B is a positive quantity, the damping of motor or generator has the sign of $(x_q \tan \delta' - r)$. Therefore, to obtain positive damping in a motor, where δ' is negative, B must be a negative quantity.

Fig. 7 is similar to Fig. 6 and is based on Equations (61) and (47); but the four curves are for different amounts of excitation; namely, $e_d' = 0.25$, $e'_d = 0.5$, $e_d' = 1$, and $e_d' = 1.5$. The armature resistance is $r = 0.1$ for all the curves. The other constants are the same as for Fig. 6. These curves bring out the fact that the general deductions as to damping based on Fig. 6 are

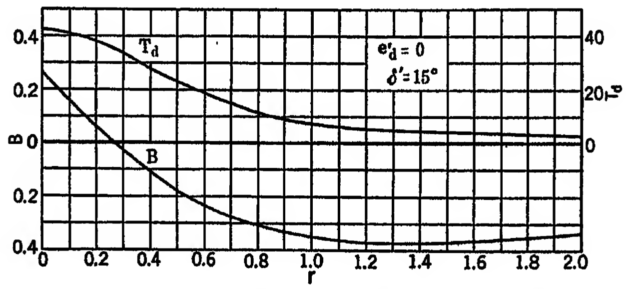

Fig. 5—Curves of Damping Torque and Factor B as Functions of Armature Resistance

Conditions same as for Curve A, Fig. 4, except that the excitation is zero and the field winding is short-circuited

independent of the value of the excitation in the range covered. Calculations show that the constant B can become negative in the generator range of load only for exceedingly low values of excitation.

Damping at Zero Load

The design engineer is occasionally asked if an amortisseur winding will prevent some particular generator from hunting. The generator will probably have been in service for some years, and the instability develops when the machine is used under new

conditions. The new conditions may be brought about by connecting it to a power system through a transmission line. The problem is to determine whether an amortisseur winding can be added which can be guaranteed to make the machine run without hunting.

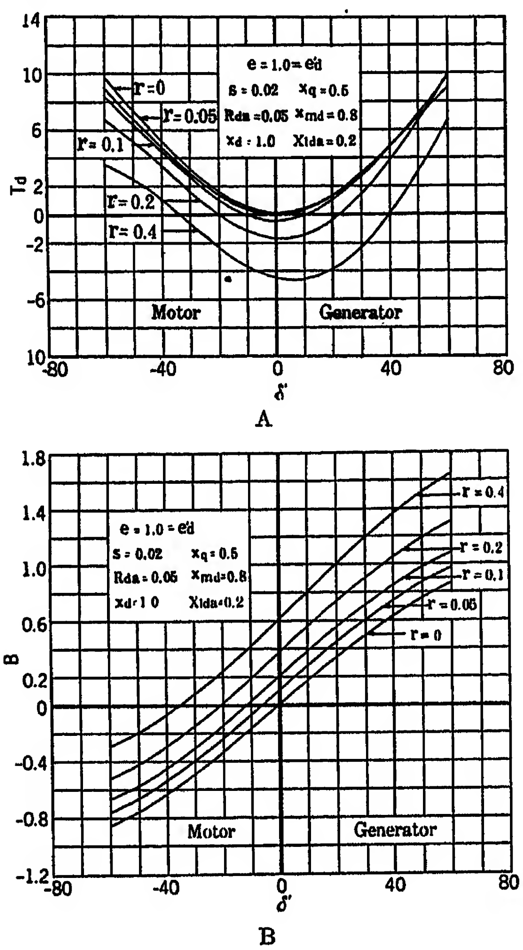

Fig. 6—Curves of Damping Torque and the Factor B as Functions of Load Angle with Armature Resistance as a Parameter. Constant Excitation and No Amortisseur Winding

A study of Equation (**56**) shows that if the damping of a generator is positive at zero displacement angle, it will remain positive at all angles. Thus the problem can be reduced to adding an amortisseur winding which will eliminate hunting under no-load conditions. Equation (**56**), when used to determine the value of the damping torque at zero load, gives an indeterminate form which must be evaluated. Equations (**56**) for damping torque, T_d, (**41**) for $\cot \alpha$, and (**50**) for the constant D, can be combined for the condition $e_d' = e$, *i. e.*, for normal excitation, to give a determinate result at no load.

The equation thus obtained is

$$T_d = -\frac{e^2}{s}\left[\frac{b\,r^2 - b^2\,d - d\,(x_d - a)^2}{[b(x_q - c) + d(x_d - a)]^2 + [b\,d - r^2 - (x_q - c)(x_d - a)]^2}\right] \qquad (64)$$

This equation shows that the critical value of armature resistance for zero damping can be found by equating the numerator to zero; giving

$$r = \sqrt{b\,d + \frac{d}{b}\,(x_d - a)^2} \qquad (65)$$

If the armature resistance is less than this critical value, the damping is positive. Thus the condition for no sustained or cumulative hunting is

$$r < \sqrt{b\,d + \frac{d}{b}\,(x_d - a)^2} \qquad (66)$$

As an example of the use of Equation (**64**), an old three-phase salient-pole synchronous generator, rated at 312 kw. and 2300 volts, became unstable on fractional loads when connected to a power system. It was assumed that the point at which the generator is connected to the system could be considered to be an infinite bus; then the combined constants of alternator

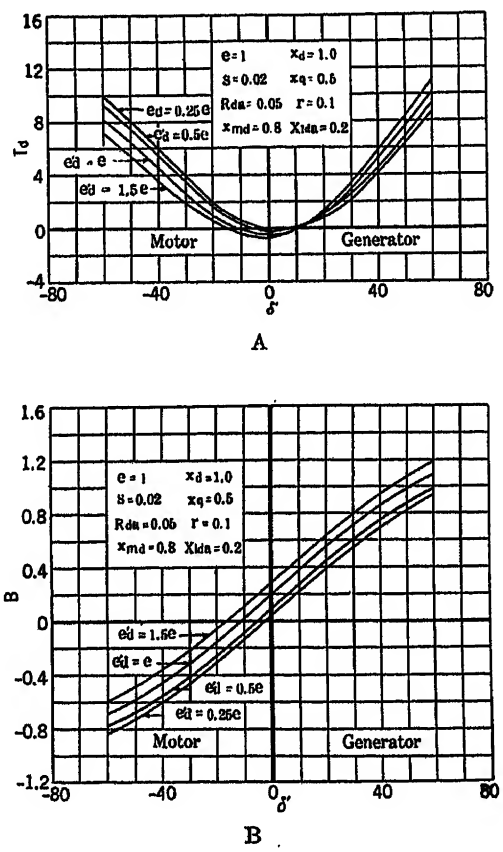

Fig. 7—Curves of Damping Torque and the Factor B as Functions of Load Angle with Excitation as a Parameter. Constant Armature Resistance and No Amortisseur Winding

and connecting line were measured and found to have the following values, *viz.*,

$x_d = 1.12$ $\quad a = 0.370$

$x_q = 0.92$ $\quad b = 0.0256$

$r = 0.73$ $\quad s = 0.04$

As the machine had no damping winding, Equation (**62**) could be used to determine whether the generator might be expected to operate without hunting. Substituting the values of the constants for the machine, Equation (**62**) shows that the machine has negative damping for all load angles below $\delta' = 38$ deg. A generator will have some positive damping due to losses in pole faces, etc.; but even with an allowance

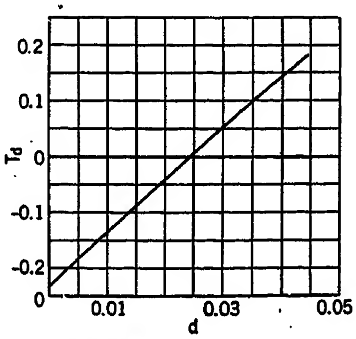

FIG. 8—VARIATION OF DAMPING TORQUE WITH THE FACTOR d FOR MACHINE RATED

for this extra damping, it seems that the generator might be expected to hunt for loads up to perhaps 50 per cent of full load.

Setting $e = 1$ in Equation (**64**), the problem is to find values of the constants (c) and (d) of an amortisseur winding which will make T_d positive. The value of (c) for a squirrel-cage winding is so small that it can be taken equal to zero without introducing serious error. Substituting the values of the constants for the machine in Equation (**64**), a relation is established between T_d and d. It is convenient to assume values of d and solve for corresponding values of T_d. The curve in Fig. 8 was plotted with values of T_d and d determined in this manner.

The curve in Fig. 8 shows that the damping torque T_d passes from negative to positive values at $d \doteq 0.024$. A damping winding can be easily designed for this machine that will give a value of d 50 per cent greater than the critical value. Thus calculations indicated that an amortisseur winding would stop the hunting, although it was never tried.

Inspection of Equation (**62**), which holds for a generator with no damping winding, suggests that T_d can be increased positively by increasing the value of x_q, the quadrature synchronous reactance of the generator. Inspection of Equation (**64**) suggests that an increase in x_d and x_q might increase T_d positively in a generator with an amortisseur winding. These values cannot be changed after a generator is built, but reactance can be added in the line. The effect of adding line inductive reactance is to increase x_d and x_q by the same amount.

The curve in Fig. 9 shows the variation of damping torque T_d of the generator for which an amortisseur winding was recommended when the line reactance is varied, if the machine is assumed to be equipped with an amortisseur winding which will make the damping torque zero, without the added line reactance. The curve is plotted between values of T_d and equivalent x_d of line and alternator for $e_d' = 1 = e$. The direct synchronous reactance of the machine is $x_d = 1.12$. The curve shows that the damping can be increased positively by adding line reactance; but the amount of positive damping that can be obtained in this manner is limited, as indicated by the curve tending to bend parallel to the x_d axis. No such limitation is found to exist when an amortisseur winding is used, as shown by the curve in Fig. 8, where T_d is seen to increase in direct proportion with the constant d of the amortisseur winding.

EXPERIMENTAL VERIFICATION OF MATHEMATICAL ANALYSIS

The verification can be divided into two parts, *viz.*, qualitative and quantitative. The first tests were made with a three-phase, four-pole, 15-kw., 1800-rev. per min., 220-volt salient-pole synchronous machine connected to a bus of relatively large power capacity. The machine was used both as motor and generator, being direct connected to a d-c. machine which was used as generator or motor, as needed. The synchronous machine could be made to hunt either as motor or generator by adding sufficient resistance in the line wires connecting the a-c. machine and bus. Most of the tests were made using the a-c. machine to drive the d-c. machine, which was loaded with a resistor. At first the power of the d-c. machine was fed back into a d-c. system, but this arrangement added so much damping that the a-c. machine was made relatively stable under all conditions.

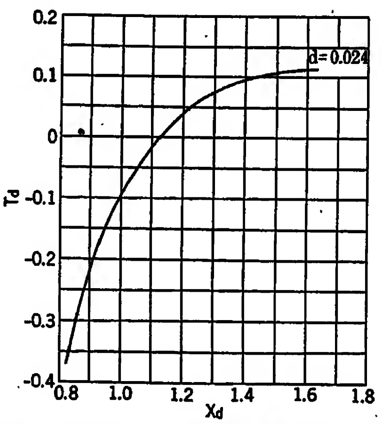

FIG. 9—CURVE SHOWING EFFECT OF LINE REACTANCE ON DAMPING TORQUE. SAME MACHINE AS FOR FIG. 8

A series of tests was run to show the effect of varying the excitation with a constant value of armature line resistance and with a constant input of 6 kw. to the synchronous motor. The line resistance was chosen of such value that one extreme of excitation gave high positive damping and the other extreme gave high negative damping. Hunting was determined by inspecting indicating instruments connected in the a-c. leads and by taking oscillograms of armature and field

currents. An excitation of 1.100, the per unit system, gave high negative damping; an excitation of 0.641 gave high positive damping. An excitation of 0.458 gave so high positive damping that an initial swing was damped out aperiodically. Critical excitation was 0.814. As the excitation was increased over this value, the damping became negative and of increasing value; as the load is increased, the value of excitation necessary to just make the machine stable also increases.

As a quantitative check, the critical excitation as the load is changed was determined by test and compared with values determined by substituting constants of the machine in equations developed by the mathematical analysis. The broken curve in Fig. 12 shows

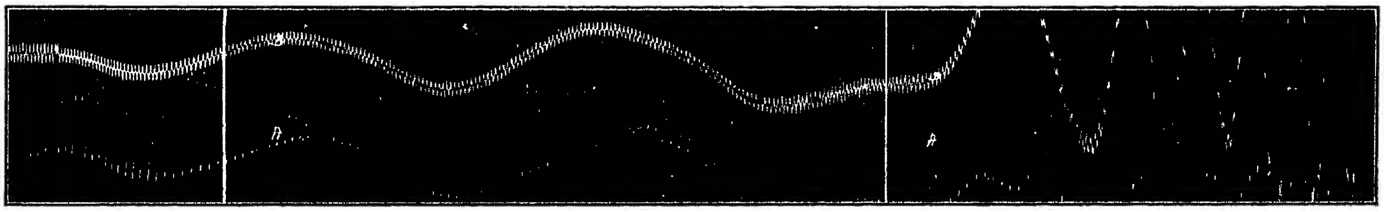

Fig. 10—Oscillogram Showing Cumulative Hunting Produced by Introduction of Resistance in the Armature Lines of a Motor

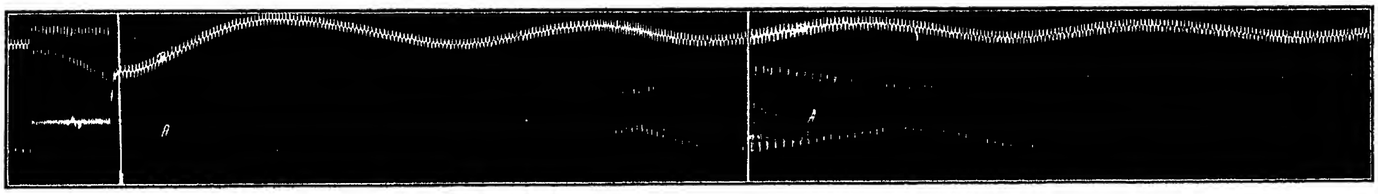

Fig. 11—Oscillogram Showing Effect of Excitation upon Damping

Conditions the same as for Fig. 10 except that excitation was reduced from 1.1 to 0.733.

curve (a)—armature current
curve (b)—field current

as decreased, the damping became positive and of increasing value. The degree of positive damping was judged by the time it took an oscillation started by a definite impulse to die away, or to become of constant amplitude. The degree of negative damping was judged either by the amount of hunting developed, or by the time it took the machine to drop out of step, after the extra line resistance was connected into the circuit.

The oscillogram in Fig. 10 indicates the degree of cumulative hunting when the excitation was 1.1. The machine started hunting as the extra line resistance was connected into the circuit. The oscillogram in Fig. 11 for an excitation of 0.733 shows positive damping; but the damping is small enough so that there is practically sustained hunting.

Further tests showed that the value of excitation which would just make the motor stable for a constant value of line resistance increased as the load was increased. That tests would show these results could be anticipated from the mathematical analysis of damping torque. In Fig. 7A, where load can be assumed proportional to displacement angle δ', since the curves are for a salient-pole machine, the curves for negative values of δ', the motor range, show that with a constant load damping increases positively with a decrease in excitation. And furthermore, these curves show that the test results; the solid curve the theoretical results. It was not expected that these two curves would coincide because of the extra damping in the motor and connected d-c. generator. Further tests showed that the greater part of the extra damping was due to the

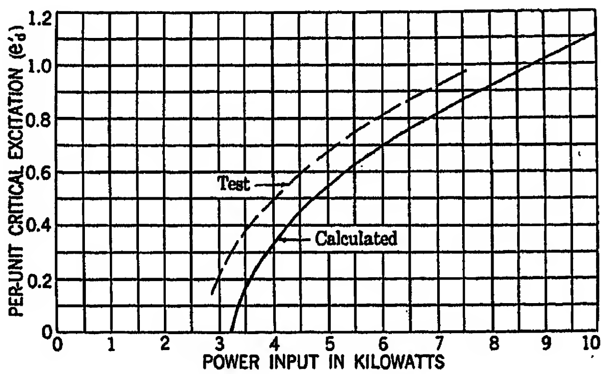

Fig. 12—Test and Calculated Curves of Excitation, for Zero Damping, as a Function of Power Input. Armature Resistance Constant

d-c. generator and did not vary with load. The amount of this constant extra damping was not determined; but inspection of Fig. 12 shows that if the whole calculated curve, the solid curve, is moved up on the sheet by a constant amount, the two curves can be made to come

into fairly close agreement. That extra damping will raise the solid curve in Fig. 12 is seen to be true by inspection of Fig. 7A, which shows that if the damping torque T_d is increased by a constant amount, higher excitation will be needed to produce a given amount of negative damping for a constant load.

A further quantitative check will be found under Hunting of Round-Rotor Synchronous Machines.

Hunting of Round-Rotor Synchronous Machines

The mathematical analysis, with $x_d = x_q$, indicates that a round-rotor synchronous machine can be made unstable by increasing the armature resistance. For a round-rotor machine symmetrical with respect to both axes, Equation (66) becomes,

$$r < \sqrt{b^2 + (x_d - a)^2} \tag{67}$$

since $b = d$. To show by test that such a machine can be made unstable by adding line resistance, a 20-hp. induction motor, with wound rotor as well as wound stator, was run as a synchronous motor. The rotor was wound two-phase, and d-c. excitation was supplied to both phases of the rotor from a storage battery. This machine with not too high excitation was very stable with minimum resistance between stator and a-c. bus; but it could be made very unstable without changing the excitation by increasing the a-c. line resistance sufficiently. Using adjustable resistors in the line, the degree of stability or instability was under complete control. With sufficient line resistance, the machine was so unstable that it could not be kept on the line.

Summary

The results given in the paper show that the calculated curves of negative damping under various conditions of loading, excitation, etc., are in essential agreement with results obtained from test. The calculated curves are correct in form and the magnitudes check test values reasonably well to allow of practical accuracy in the use of the general expressions developed in the paper. More recent tests further confirm the theoretical formulas.

This article furnishes an explanation for those many cases encountered in the field in which machines cannot be kept in synchronism when operated over long lines, or are unstable for no apparent reason.

Acknowledgments

The authors gratefully acknowledge the valuable assistance of Messrs. S. R. Pritchard, Jr., R. C. Small, and S. A. Loukomsky in the preparation of experimental data on the salient pole machine. They also wish to acknowledge the helpful suggestions of Messrs. R. E. Doherty and R. H. Park.

Appendix I

MATHEMATICAL ANALYSIS

Determination of the Phase Angle α

The mathematical analysis which follows is divided into two parts. The value of the phase angle α, which is the angle between the currents induced in the rotor windings in the direct and quadrature axes by the modulated armature current, will be derived first. Then the values of the damping and synchronizing components of torque will be determined.

Referring to Fig. 2, which shows the peak values of armature voltage and current for a salient-pole synchronous generator with no excitation in the quadrature axis, it is seen that the nominal voltages are

$$e_d = e \cos \delta + i_q r + i_d x_d \tag{6}$$

and,

$$e_q = i_q x_q - e \sin \delta - i_d r = 0 \tag{7}$$

where r is armature resistance, x_d and x_q are the direct and quadrature synchronous reactances, and e is terminal voltage.

Since the modulation is assumed to be slow enough so that the voltage and current are accurately represented at each instant by vectors, as in Fig. 2, Equations (1), (2), (3), and (5) may be substituted in (6) giving

$$e \cos \delta' \cos [\Delta \delta] - e \sin \delta' \sin [\Delta \delta]$$
$$= e_d' + [\Delta e_d] - i_q' r - [\Delta i_q] r - i_d' x_d - [\Delta i_d] x_d \tag{8}$$

If the alternating component of the displacement angle is assumed to be small, meaning that the rotor hunts through a small angle, then at any instant

$$\cos [\Delta \delta] = 1 \tag{9}$$

and

$$\sin [\Delta \delta] = [\Delta \delta] \tag{10}$$

Substituting (9) and (10) in (8) and solving, the alternating component of the torque angle is

$$[\Delta \delta] = \frac{e \cos \delta' - e_d' + i_q' r + i_d' x_d - [\Delta e_d] + [\Delta i_q] r + [\Delta i_d] x_d}{e \sin \delta'} \tag{11}$$

The vector diagram in Fig. 2 shows that

$$e \cos \delta' - e_d' + i_q' r + i_d' x_d = 0 \tag{12}$$

whence (11) reduces to

$$[\Delta \delta] = \frac{[\Delta i_q] r + [\Delta i_d] x_d - [\Delta e_d]}{e \sin \delta'} \tag{13}$$

Substituting the values given in (1), (2), (4), and (5) in (7),

$$e \sin \delta' \cos [\Delta \delta] + e \cos \delta' \sin \Delta \delta$$
$$= i_q' x_q + [\Delta i_q] x_q - i_d' r - [\Delta i_d] r - [\Delta e_q] \tag{14}$$

Substituting (9) and (10) in (14) and solving for the modulating angle,

$$[\Delta \delta] = \frac{i_q' x_q - i_d' r - e \sin \delta' + [i_q] x_q - [\Delta i_d] r - [\Delta e_q]}{e \cos \delta'} \tag{15}$$

The vector diagram in Fig. 2 shows that

$$i_q' x_q - i_d' r - e \sin \delta' = 0 \tag{16}$$

whence (15) reduces to

$$[\Delta \delta] = \frac{[\Delta i_q] x_q - [\Delta i_d] r - [\Delta e_q]}{e \cos \delta'} \tag{17}$$

The modulating components of the direct component of current i_d and the quadrature component i_q, from (1) and (2), are

$$[\Delta i_d] = \Delta i_d \cos s t \tag{18}$$

and

$$[\Delta i_q] = \Delta i_q \cos (s t + \alpha) \tag{19}$$

Changing from instantaneous to vector notation, and choosing $[\Delta i_d]$ as the reference vector, (18) and (19) become

$$\Delta \dot{i}_d = \Delta i_d < 0 = \Delta i_d \tag{20}$$

and,

$$\Delta \dot{i}_q = \Delta i_q < \alpha = \Delta i_q (\cos \alpha + j \sin \alpha) \tag{21}$$

These modulating components of current flow in the armature windings and induce alternating components of current $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$, in the two field windings. It has been shown[1b] that

$$\Delta \dot{I}_d = \Delta \dot{i}_d (a + j b) = \Delta i_d (a + j b) \tag{22}$$

and

$$\Delta \dot{I}_q = \Delta \dot{i}_q (c + j d) \tag{23}$$

where the values of the constants are

$$a = \frac{s^2 x_{md}^2 (x_{md} + X_{lda})}{R_{da}^2 + s^2 (x_{md} + X_{lda})^2} = \frac{(x_d - x_d') s^2 T_{do}^2}{1 + s^2 T_{do}^2} \tag{24}$$

$$b = \frac{s x_{md}^2 R_{da}}{R_{da}^2 + s^2 (x_{md} + X_{lda})^2} = \frac{(x_d - x_d') s T_{do}}{1 + s^2 T_{do}^2} \tag{25}$$

$$c = \frac{s^2 x_{mq}^2 (x_{mq} + X_{lqa})}{R_{qa}^2 + s^2 (x_{mq} + X_{lqa})^2} = \frac{(x_q - x_q') s^2 T_{qo}^2}{1 + s^2 T_{qo}^2} \tag{26}$$

$$d = \frac{s x_{mq}^2 R_{qa}}{R_{qa}^2 + s^2 (x_{mq} + X_{lqa})^2} = \frac{(x_q - x_q') s T_{qo}}{1 + s^2 T_{qo}^2} \tag{27}$$

$$\frac{x_{md} + X_{lda}}{R_{da}} = T_{do} \text{ and } x_{md}^2 = (x_{md} + X_{lda})(x_d - x_d')$$

In these equations $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$ are the alternating currents in the two field windings, x_{md} and x_{mq} are the mutual reactances between the armature winding and the two field windings, X_{lda} and X_{lqa} are the leakage reactances of the two field windings in armature terms, and R_{da} and R_{qa} are the resistances of the two field windings in armature terms, R_{da} including the resistance of the armature circuit of the exciter.

The modulating components of field current, $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$, induce modulating components of nominal voltage, $\Delta \dot{e}_d$ and $\Delta \dot{e}_q$, therein. Using per unit quantities,

$$\Delta \dot{e}_d = \Delta \dot{I}_d \tag{28}$$

and

$$\Delta \dot{e}_q = \Delta \dot{I}_q \tag{29}$$

Substituting these values of $\Delta \dot{I}_d$ and $\Delta \dot{I}_q$ in (22) and (23),

$$\Delta \dot{e}_d = \Delta \dot{i}_d (a + j b) \tag{30}$$

and

$$\Delta \dot{e}_q = \Delta \dot{i}_q (c + j d) \tag{31}$$

Substituting (20) in (30) and (21) in (31),

$$\Delta \dot{e}_d = \Delta i_d (a + j b) \tag{32}$$

$$\Delta \dot{e}_q = \Delta i_q (c + j d) (\cos \alpha + j \sin \alpha)$$

$$= \Delta i_q [c \cos \alpha - d \sin \alpha + j (c \sin \alpha + d \cos \alpha)] \tag{33}$$

These equations determine the values of the modulated nominal voltages in the direct and quadrature axes in terms of the corresponding modulating components of current.

Writing (13) in vector notation, the value of the alternating component of the torque angle is

$$\Delta \dot{\delta} = \frac{\Delta \dot{i}_q r + \Delta \dot{i}_d x_d - \Delta \dot{e}_d}{e \sin \delta'} \tag{34}$$

Substituting (20), (21), and (32) in (34),

$$\Delta \dot{\delta} = \frac{\Delta i_q r \cos \alpha + \Delta i_d x_d - \Delta i_d a + j(\Delta i_q r \sin \alpha - \Delta i_d b)}{e \sin \delta'} \tag{35}$$

Changing (17) to vector notation,

$$\Delta \dot{\delta} = \frac{\Delta \dot{i}_q x_q - \Delta \dot{i}_d r - \Delta \dot{e}_q}{e \cos \delta'} \tag{36}$$

Substituting (20), (21), and (33) in (36),

$$\Delta \dot{\delta} = \frac{\Delta i_q x_q \cos \alpha - \Delta i_d r - \Delta i_q (c \cos \alpha - d \sin \alpha)}{e \cos \delta'} + j \frac{\Delta i_q x_q \sin \alpha - \Delta i_q (c \sin \alpha + d \cos \alpha)}{e \cos \delta'} \tag{37}$$

Equations (35) and (37) give two relations for $\Delta \dot{\delta}$. Equating the real terms in the two equations,

$$\frac{\Delta i_q r \cos \alpha + \Delta i_d x_d - \Delta i_d a}{e \sin \delta'} = \frac{\Delta i_q [(x_q - c) \cos \alpha + d \sin \alpha] - \Delta i_d r}{e \cos \delta'} \tag{38}$$

and equating the imaginary terms in the same two equations,

$$\frac{\Delta i_q r \sin \alpha - \Delta i_d b}{e \sin \delta'} = \frac{\Delta i_q [(x_q - c) \sin \alpha - d \cos \alpha]}{e \cos \delta'} \tag{39}$$

Solving (39) for the alternating component of the armature current in the direct axis,

$$\Delta i_d = \Delta i_q \left[\frac{r \sin \alpha}{b} - \frac{\{(x_q - c) \sin \alpha - d \cos \alpha\} \tan \delta'}{b} \right] \tag{40}$$

Substituting (40) in (38), the value of the phase angle α is determined as

$$\cot \alpha = \frac{[b\, d - r^2 + (x_d - a)(x_q - c)] \tan \delta' - r(x_d - a) + r(x_q - c) \tan^2 \delta'}{[d\, (x_d - a) - b\, (x_q - c)] \tan \delta' + b\, r + d\, r \tan^2 \delta'} \tag{41}$$

Determination of Damping and Synchronizing Torques

Equations for the electrical output and armature copper loss of a synchronous machine connected to an

infinite bus have been previously developed.[1a] Since in the per unit system of units torque and power are numerically equal, if the angular velocity of rotation is substantially constant at normal value, these equations can be used to determine torque. Letting T represent the torque due to the combined electrical output and copper loss in the machine,

$$T = \frac{(e\,e_d e_q - e\,e_q r)\sin\delta + (e\,e_d r + e\,e_q x_d)\cos\delta + \frac{e^2}{2}(x_d - x_q)\sin 2\delta - e^2 r}{r^2 + x_d x_q} + \frac{r(r^2+x_q^2)(e_d - e\cos\delta)^2 + r(r^2+x_d^2)(e_q + e\sin\delta)^2}{(r^2 + x_d x_q)^2} + \frac{2 r^2 (x_d - x_q)(e_d - e\cos\delta)(e_q + e\sin\delta)}{(r^2 + x_d x_q)^2} \quad (42)$$

where the term with $r^2 + x_d x_q$ in the denominator is the torque corresponding to the electrical output, and the other terms give the torque corresponding to copper loss in the armature.

The modulation of angular velocity of the machine causes a modulation $[\Delta T]$ of the steady-value torque T', so that the torque at any instant is

$$T = T' + [\Delta T] \quad (43)$$

The value of T may be found by substituting (3), (4), and (5) in (42) and then placing $\cos[\Delta\delta] = 1$ and $\sin[\Delta\delta] = [\Delta\delta]$, which means that the machine is assumed to hunt through a small angle only. Making the substitutions indicated, neglecting all products such as $[\Delta e_d] \times [\Delta\delta]$, because they are infinitesimals of second order, the remaining terms may be grouped to give T' and $[\Delta T]$. The value of the alternating component of torque is

$$[\Delta T] = \frac{e\,e_d' x_q[\Delta\delta]\cos\delta' + e\,x_q[\Delta e_d]\sin\delta' - e\,r[\Delta e_q]\sin\delta'}{r^2 + x_d x_q} + \frac{e\,e_d' r[\Delta\delta]\sin\delta' + e\,r[\Delta e_d]\cos\delta' + e\,x_d[\Delta e_q]\cos\delta'}{r^2 + x_d x_q} + \frac{e^2 (x_d - x_q)[\Delta\delta]\cos 2\delta'}{r^2 + x_d x_q} + \frac{r(r^2 + x_q^2)[[\Delta e_d](2 e_d' - 2e\cos\delta') + [\Delta\delta](2 e\,e_d'\sin\delta' - 2e^2\sin\delta'\cos\delta')]}{(r^2 + x_d x_q)^2} + \frac{r(r^2 + x_d^2)[2[\Delta e_q]e\sin\delta' + 2e^2[\Delta\delta]\sin\delta'\cos\delta']}{(r^2 + x_d x_q)^2} + \frac{2r^2(x_d - x_q)[[\Delta e_q](e_d' - e\cos\delta') + [\Delta e_d]e\sin\delta' + [\Delta\delta](e^2\sin^2\delta' - e^2\cos^2\delta' + e\,e_d'\cos\delta')]}{(r^2 + x_d x_q)^2} \quad (44)$$

Changing the quantities $[\Delta T]$, $[\Delta\delta]$, $[\Delta e_d]$, and $[\Delta e_q]$ to vector notation and collecting terms, (44) becomes

$$\Delta \dot{T} = A\,\Delta\dot{\delta} + B\,\Delta\dot{e}_d + C\,\Delta\dot{e}_q \quad (45)$$

where the constants A, B, and C have the following values:

$$A = \frac{e\,e_d'(x_q\cos\delta' - r\sin\delta') + e^2(x_d - x_q)\cos 2\delta'}{r^2 + x_d x_q} + \frac{2r(r^2 + x_q^2)(e\,e_d'\sin\delta' - e^2\sin\delta'\cos\delta') + 2r(r^2 + x_d^2)e^2\sin\delta'\cos\delta'}{(r^2 + x_d x_q)^2} + \frac{2r^2(x_d - x_q)(e^2\sin^2\delta' - e^2\cos^2\delta' + e\,e_d'\cos\delta')}{(r^2 + x_d x_q)^2} \quad (46)$$

$$B = \frac{e(x_q\sin\delta' + r\cos\delta')}{r^2 + x_d x_q} + \frac{2r(r^2+x_q^2)(e_d' - e\cos\delta') + 2r^2(x_d - x_q)e\sin\delta'}{(r^2 + x_d x_q)^2} \quad (47)$$

$$C = \frac{e(x_d\cos\delta' - r\sin\delta')}{r^2 + x_d x_q} + \frac{2r(r^2+x_d^2)e\sin\delta' + 2r^2(x_d - x_q)(e_d' - e\cos\delta')}{(r^2 + x_d x_q)^2} \quad (48)$$

A physical meaning can be ascribed to the constants A, B, and C if they are derived directly by differentiation. The complete differential of T in (42) is,

$$dT = \frac{\partial T}{\partial\delta}d\delta + \frac{\partial T}{\partial e_d}de_d + \frac{\partial T}{\partial e_q}de_q$$

$$= A\,d\delta + B\,de_d + C\,de_q$$

which can be written

$$d\dot{T} = A\,\Delta\delta + B\,\Delta\dot{e}_d + C\,\Delta e_q$$

to correspond to the form used in Equation (45). Thus the constant A is equal to the variation in the torque T when the angle δ is varied and the voltages e_d and e_q are held constant. Similar meanings can be ascribed to the constants B and C.

Equation (40) can be written in the form,

$$\Delta i_d = D\,\Delta i_q \quad (49)$$

where the constant D has the value

$$D = \frac{r\sin\alpha}{b} - \frac{[(x_q - c)\sin\alpha - d\cos\alpha]\tan\delta'}{b} \quad (50)$$

Substituting (49) in (30),

$$\Delta\dot{e}_d = D\,\Delta i_q(a + jb) \quad (51)$$

Substituting (49) in (35),

$$\Delta\dot{\delta} = \Delta i_q\left[\frac{r\cos\alpha + D(x_d - a) + j(r\sin\alpha - bD)}{e\sin\delta'}\right] \quad (52)$$

Substituting (51), (33), and (52), in (45), the value of the alternating component of the torque is

$$\Delta \dot{T} = A \, \Delta \dot{i}_q \left[\frac{r \cos \alpha + D(x_d - a) + j(r \sin \alpha - b\,D)}{e \sin \delta'}\right]$$

$$+ B\,D\,\Delta \dot{i}_q\,(a + j\,b)$$

$$+ C\,\Delta \dot{i}_q\,[(c \cos \alpha - d \sin \alpha) + j\,(c \sin \alpha + d \cos \alpha)]$$

$$= \frac{A\,\Delta \dot{i}_q\,[r \cos \alpha + D\,(x_d - a)]}{e \sin \delta'}$$

$$+ B\,D\,a\,\Delta \dot{i}_q + C\,\Delta \dot{i}_q\,(c \cos \alpha - d \sin \alpha)$$

$$+ j\left[\frac{A\,\Delta \dot{i}_q\,[r \sin \alpha - b\,D]}{e \sin \delta'}\right.$$

$$\left. + B\,D\,b\,\Delta \dot{i}_q + C\,\Delta \dot{i}_q\,(c \sin \alpha + d \cos \alpha)\right] \quad (53)$$

The damping and synchronizing components of torque may be determined from the electromagnetic motional impedance[1b] of the generator to hunting. The real part of the vector expression for motional impedance is equal to the damping torque T_d, and the imaginary part is equal to $-\dfrac{T_s}{s}$ where T_s is the synchronizing torque. The motional impedance $\dot{Z}_m$ can be found by dividing the alternating component of torque $\Delta \dot{T}$ by the corresponding angular velocity $\dot{\omega}_1$ of hunting. The angular velocity can be found as the time rate of change of the alternating component, $\Delta \dot{\delta}$, of displacement angle. Thus differentiating (52) with respect to time,

$$\dot{\omega}_1 = \frac{d}{d\,t}\,\Delta \dot{\delta}$$

$$= -\,s\,\Delta \dot{i}_q \left[\frac{(r \sin \alpha - b\,D) - j\,[r \cos \alpha + D\,(x_d - a)]}{e \sin \delta'}\right] \quad (54)$$

The motional impedance is, then,

$$\dot{Z}_m = \frac{\Delta \dot{T}}{\dot{\omega}_1} = T_d - j\,\frac{T_s}{s} \quad (55)$$

Now dividing (53) by (54), the damping torque is

$$T_d = \frac{B\,D\,e \sin \delta'\,[D\,b\,x_d + r\,(b \cos \alpha - a \sin \alpha)]}{s\,[(r \sin \alpha - b\,D)^2 + \{r \cos \alpha + D(x_d - a)\}^2]}$$

$$+ \frac{C\,e \sin \delta'\,[D\,b\,(c \cos \alpha - d \sin \alpha) + D\,(x_d - a)\,(c \sin \alpha + d \cos \alpha) + r\,d]}{s[(r \sin \alpha - b\,D)^2 + \{r \cos \alpha + D(x_d - a)\}^2]} \quad (56)$$

and the synchronizing torque is

$$T_s = T_s'$$

$$+ \frac{B\,D\,e \sin \delta'[D\{a(x_d - a) - b^2\} + r(a \cos \alpha + b \sin \alpha)]}{(r \sin \alpha - b\,D)^2 + \{r \cos \alpha + D(x_d - a)\}^2}$$

$$+ \frac{C\,e \sin \delta'\,[D\,\{c\,(x_d - a) - b\,d\} \cos \alpha - D\,\{d\,(x_d - a) + b\,c\} \sin \alpha + r\,c]}{(r \sin \alpha - b\,D)^2 + \{r \cos \alpha + D\,(x_d - a)\}^2} \quad (57)$$

where T_s' is equal to the synchronizing torque at the average displacement angle δ' due to steady-state conditions. It is interesting to note that the synchronizing torque of a machine in a sustained state of oscillation is equal to the value for zero frequency of oscillation, *i. e.*, steady-state value, plus an increment which is a function of the actual frequency of oscillation. Equation (56) gives the value of the damping torque of a polyphase synchronous machine which is connected to a bus with large enough power capacity to maintain the bus voltage constant when the machine hunts. The damping is assumed to be due entirely to currents induced in the main field winding in the direct axis and in the amortisseur winding in the quadrature axis by the modulated armature currents.

Nomenclature

Peak values are used for voltage and current. Primed quantities indicate steady-state values. The symbol Δ indicates variation of the quantity which follows the symbol. Per unit values are used for all equations and numerical work.

e = terminal voltage.
e_d = nominal voltage due to excitation in the direct axis.
e_q = nominal voltage due to excitation in the quadrature axis.
i = armature current.
i_d = direct component of armature current.
i_q = quadrature component of armature current.
I_d = field current, direct axis, in field terms.
I_q = field current, quadrature axis, in field terms.
t = time.
s = angular velocity of modulation.
ω_1 = angular velocity hunting.
ω = angular velocity at line frequency.
r = armature circuit resistance; includes resistance of line wire, back to the infinite bus.
R_{da} = field resistance, direct axis, in armature terms.
R_{qa} = field resistance, quadrature axis, in armature terms.
x_d = synchronous reactance, direct axis includes reactance of line wire back to the infinite bus.
x_q = synchronous reactance, quadrature axis; includes reactance of line wire back to the infinite bus.
x_{md} = mutual reactance, direct axis.
x_{mq} = mutual reactance, quadrature axis.
X_{lda} = field leakage reactance, direct axis, in armature terms.
X_{lqa} = field leakage reactance, quadrature axis, in armature terms.
T = torque.
T_d = damping torque.

T_s = synchronizing torque.
α = time phase displacement between direct and quadrature components of modulated armature current.
δ = angular displacement between the axes of rotor and rotating magnetic field; a plus angle indicates generator; a negative angle indicates motor.
Z_m = electromagnetic motional impedance.
a = see Formula 24.
b = see Formula 25.
c = see Formula 26.
d = see Formula 27.

$$A = \frac{\partial T}{\partial \delta}, \text{ if } e_d \text{ and } e_q \text{ are held constant.}$$

$$B = \frac{\partial T}{\partial e_d}, \text{ if } \delta \text{ and } e_q \text{ are held constant.}$$

$$C = \frac{\partial T}{\partial e_q}, \text{ if } \delta \text{ and } e_d \text{ are held constant.}$$

$$D = \Delta i_d / \Delta i_q.$$

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Discussion

C. F. Wagner: (communicated after adjournment) From time to time an occasional case of spontaneous hunting arises, the cause of which can be traced to an excessive proportion of resistance in the armature circuit, *viz.*, in the transmission line. This phenomenon was particularly evident in the early days of rotary converters. A rough working rule in use at that time was to limit the line resistance to 25 per cent of the reactance. As has been pointed out by the authors, Dreyfus[1] in 1911 showed that the tendency toward hunting decreased with increasing load and with smaller excitation and that the presence of damper windings alleviated this condition. Tests were made on an induction motor to check his theory. In 1924, reporting stability tests made in the works of the Westinghouse Company, Evans and Bergvall[2] likewise demonstrated this same effect using salient-pole generators and condensers. More recently Wennerberg[3] analyzed the same problem as applied to salient pole machines, extending it to include the effect of exciters. Nickle and Pierce in the paper under discussion attack the problem in a somewhat different manner and arrive at some very interesting and simple results. I have also done some work recently of a similar nature and with a somewhat different method of attack which I believe possesses the advantage of a clearer conception of the mechanism involved.

To illustrate the method I shall merely apply the analysis in a qualitative manner to a salient-pole generator without damper windings connected to an infinite bus through a transmission line whose resistance will be varied. Constant excitation of the generator will be assumed. The transient analysis of synchronous machines may be expedited by the use of the so-called "transient reactance" (x_d') and the "transient internal voltage" (e_d'), which will be defined as the terminal voltage plus the transient reactance drop at zero power factor. For any other power factor the components in the direct axis must be used. This is the fictitious voltage corresponding to flux linkages with the field, and which remains unchanged for any sudden change in circuit condition. The voltage e_d will be defined in a similar manner except that the synchronous reactance x_d must be used. For steady-state conditions

$$e_d' = e_d - (x_d - x_d')\, i_d$$

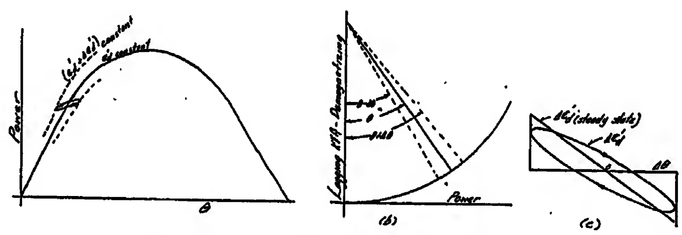

FIG. 1—PURE LINE RESISTANCE

in which i_d is the component of armature current in lagging quadrature with e_d and e_d', *i. e.*, it is the demagnetizing component of current.

Consider first the line without resistance. For a given value of e_d' the power-angle curve is somewhat as shown in Fig. 1a herewith. For small positive increments in e_d' the resultant curve will, for nearly all practical cases, lie above the one for e_d'. Now assume the generator to be operating at the angle θ, and that the power input from the water wheel is such as to produce a small sinusoidal oscillation of magnitude $\Delta\,\theta_m$ and frequency f. The power-reactive power diagram (similar to the well known power-circle diagram except for effects of saliency) for constant e_d is shown in Fig. 1b and it will be observed that for positive increments in θ the demagnetizing current, i_d, increases so that the steady-state value of e_d' decreases. This relation is shown by the straight line in Fig. 1c which indicates that for positive values of $\Delta\,\theta$, $\Delta\, e_d'\,_{(steady\ state)}$ is negative. If the frequency of oscillation were very slow these are the values which $\Delta\, e_d'$ would attain. However, in the actual case, due to the time constant of the field circuit, the instantaneous value of $\Delta\, e_d'$ lags, forming the elliptical loop shown in Fig. 1c. It can further be seen that the motion around the loop is clockwise. Having obtained the instantaneous values of

1. See bibliography (2) of paper.
2. *Experimental Analysis of Stability and Power Limitations*, by R. D. Evans and R. C. Bergvall, A. I. E. E. TRANS., Vol. XLIII, 1924, p. 39.
3. "Hunting Characteristics of Synchronous Machines for Oscillations of Small Amplitude," by John Wennerberg, *A.S.E.A. Jl.*, April-May, 1929.

$\Delta e_d'$ as a function of the angle, the instantaneous power-angle relations may be obtained, resulting in the power loop indicated in Fig. 1a, the generating point of which also rotates clockwise around the loop. It can be shown that the area of this loop represents the energy per cycle which must be supplied by the variations in generator input to sustain such oscillations or the energy per cycle which would be absorbed in damping out the oscillations were they once started. It represents a stable operating condition.

Now if the resistance be placed in the line, the power-angle diagram will have the same general shape but the power-reactive power diagram is changed radically as shown in Fig. 2b herewith. It will be observed that for the particular operating angle shown, a positive increment in θ decreases the demagnetizing effect, so that the steady state value of $\Delta e_d'$, the value which $\Delta e_d'$ tends to approach, increases with $\Delta \theta$. The lag due to the time constant now produces a loop in which the generatting point rotates counter-clockwise, resulting in a power loop in which the generating point also rotates counter-clockwise. The area of the power loop now represents the energy per cycle input into the vibrating system and represents an unstable condition. The slightest disturbance results in a condition of "hunting."

As the operating angle, about which the oscillations occur, is increased, a point is reached when no change in demagnetizing current occurs for small changes in θ and beyond this point the conditions are the same as for the case in which the resistance in the armature is zero, that is, the operation is again stable.

C. A. Nickle: The explanation of negative damping of synchronous machines given by Mr. Wagner in his discussion is interesting and is essentially the same as expressed by the author during the presentation of the paper, *i. e.*, the demagnetizing

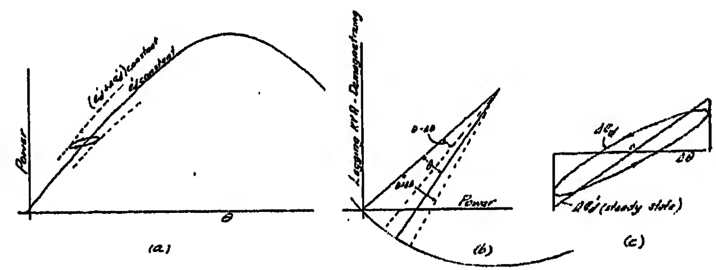

FIG. 2—LINE WITH RESISTANCE

current for a small angular oscillation changes sign for some average operating angle.

As brought out at that time, this change of sign is independent of the frequency of the oscillation. The magnitude of the damping factor does, however, depend upon the frequency of oscillation.

Ionization Currents and the Breakdown of Insulation

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Associate, A. I. E. E.

and

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Synopsis.—Certain theories of the breakdown of gases are reviewed. Their limitations or correctness in the light of recent data on the breakdown of large gaps with surge voltages are considered. The work of various investigators on the time lag of breakdown also is discussed briefly. It is shown that comparisons are made difficult and that large discrepancies, particularly at the shorter time lags, may result from variations in the definitions of time lag and breakdown time.

The existence of ionization or streamer currents of high magnitude previous to the final breakdown is established and a number of volt—time and ampere—time oscillograms of flashovers on various types of insulation is shown and discussed. The effect of these streamer currents in attenuating a traveling chopped wave is shown.

* * * * *

INTRODUCTION

ONE of the most perplexing engineering problems is the application of insulation. Continually increasing voltages and higher temperatures, together with economic requirements, have necessitated extensive development and research programs for the study of the properties of insulating materials. However, in spite of much study and ceaseless effort, no exact indisputable laws for the performance of insulation have been discovered. Empirical equations concerning particular applications have been formulated from years of experience, and it is upon these that the designer must rely. A more exact knowledge of the process of breakdown is of prime importance, since other properties of various types of insulation then could be established more readily and applied more effectively.

The dielectric strength of important types of insulation, especially air, has been determined accurately for unidirectional and for low-frequency potentials. However, these determinations have proved insufficient, since transients have caused failure in apparatus even with excessive insulation for its voltage rating. Investigators, who have used voltage impulses of extremely short duration, have shown that breakdown depends upon the rate of voltage application, the magnitude of the voltage, and the duration of the transient. Although these results have been very valuable, it was soon found that there were other considerations involved in the process of breakdown, which, if known, might aid materially in the application of insulation.

Much of the work on the breakdown of air has been done on small sphere-gaps at small spacings. From a practical and engineering standpoint it is necessary to supplement this work with experiments on apparatus where the gaps are long and irregular, with all shapes of electrodes. Entirely different breakdown characteristics may be expected with such differences in the nature of the gaps and electrodes, with the consequent change of dielectric field. In this paper a brief résumé of some of the previous theoretical work will be followed by a discussion of experimental results obtained on commercial apparatus. A new factor in the study of breakdown, heretofore used to a limited extent in the laboratory, will be introduced. The consideration of ionization or streamer currents already has proved valuable in the study of the effect of transients upon insulation.

THEORIES OF THE BREAKDOWN OF AIR

The first theory to give a satisfactory explanation of the electrical breakdown of air was advanced by Townsend.[1] Briefly this theory may be summarized as follows: Upon the application of sufficient voltage, the free electrons in the field move toward the anode and are swept out of the field. During this movement they collide with the molecules of the gas and produce new ions by collision. The newly created positive ions move toward the cathode, creating more new ions by collision, although the rate of ionization is much less than for the electrons. If the positive ions in their movement toward the cathode produce more electrons than were in the field originally, the discharge will become unstable; that is, the current will continue to increase as long as a constant impressed voltage is maintained.

Two important conclusions may be drawn from this theory. First, breakdown takes place throughout the whole field simultaneously; second, the time of breakdown cannot be any shorter than that required for the movement of an electron from one electrode to the other and for the return movement of the positive ion. Townsend's theory, although checked and proved experimentally at low pressures, appears inadequate at atmospheric pressures. Rogowski[2] has shown that the ionization process according to Townsend's theory requires a time of the order of 10^{-5} sec., whereas experimenters,[3,4] agree that with slight overvoltages the spark lag may be as short as 10^{-8} sec. Suppressed discharges[5] show that breakdown does not take place simultaneously throughout the whole field. Actually,

*Both of Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., December 2-4, 1929.

1. See Bibliography for all references.

streamers form in the most intense parts of the field and these streamers cause breakdown by developing until the two electrodes are linked.

More recently, Slepian[6] presented a new theory which accounts for the streamer currents and according to which spark lags of the order of 10^{-7} sec. may be obtained with slight overvoltages. Slepian's theory may be summarized briefly as follows: Upon the application of suitable potential, free electrons in the field move toward the anode and multiply by collision. The rapidly increasing electrons, in forcing their way through the gas, produce sufficient heat to cause thermal ionization, and a streamer is formed. This sequence takes place in the most highly stressed parts of the field, which are usually at the electrode surfaces. Immediately upon the formation of the streamer the gradient at its tip becomes very high, thus increasing its growth in the same manner in which it was formed. One end of the streamer becomes attached to the adjacent electrode; the other end develops at an increasing rate until the gap is spanned. When this occurs the gap may be said to be broken down.

Slepian's theory is based upon the mobility of the electron, and hence, the calculated breakdown time is much shorter than that obtained from theories in which the motion of the more sluggish positive ion is an important factor. However, it must be remembered, in checking these theories quantitatively, that most of the experimental data are only approximate, and at best only the order of magnitude is indicated. On the other hand, these theories serve admirably to guide the experimenter to a logical course of investigation.

A conclusion which might be drawn from both of the above theories is that appreciable currents exist prior to complete breakdown. More specifically, these currents would be expected from the rapid space charge formation of Slepian's theory and from the ionic formation and migration of Townsend's theory. Slepian and Torok[7] have shown that such currents may amount to thousands of amperes in large homogeneous fields.

The Determination of Breakdown Time

Much of the early work on sparking time has been done on sphere-gaps. Pedersen[8] impressed a flat-topped wave with an abrupt front upon a sphere-gap and determined the time lag by means of a transmission line and Lichtenberg figures. He obtained time lags of the order of 10^{-8} sec. with short gaps. Burawoy[3] has shown that the wave-front cannot be perpendicular, and hence, Pedersen's results may be somewhat in error. Peek[9] impressed a highly damped oscillatory wave upon a sphere-gap and found no appreciable time lag. In his tests the wave shape was determined entirely from the constants of the generator. Unfortunately, in many of these cases, the wave probably was distorted by the presence of a second sphere-gap in the circuit.

Burawoy used sinusoidal pulses of short duration by passing surges through a loop in a transmission line. The test gap was placed across the terminals of the loop. In analyzing the data, Burawoy used the entire wave as the time lag and the voltage crest as the breakdown potential. Results procured in this manner show that sphere-gaps separated approximately one centimeter break down in periods of time as short as 10^{-9} sec. Data also were obtained on electrodes giving less homogeneous fields; here, however, breakdown took place only with pulses of long duration.

The results obtained by Burawoy, Pedersen, and Peek have been of considerable value in determining the properties of insulation under impulses. These methods, however, can be used only indirectly in investigating the process of breakdown, as it is impossible to ascertain the part of the wave where breakdown starts or where it is complete; also nothing can be learned of the action within the field prior to breakdown.

The cathode ray oscillograph has provided a means of determining the characteristics of breakdown with great exactness; this instrument has been used extensively in Europe and in America. Tamm[4] obtained some excellent volt—time records on sphere-gaps subjected to low-voltage surges with exceedingly abrupt fronts. In interpreting his results he used the point at which the voltage exceeded the steady-state breakdown value as the initial time reference point; the point at which the voltage was suddenly reduced was taken as the breakdown point. The breakdown curve of the sphere-gap was then easily constructed, since these two points were readily established. His results show that time lag is an inverse function of the overvoltages. His experiments with gaps in various gases at low pressures are of special interest. Under these conditions a slight drop in voltage prior to breakdown indicated a preliminary discharge; Tamm expressed the opinion in his conclusions that such preliminary discharges also might occur at atmospheric pressure.

A group of tests on actual transmission line insulation was made by Smith and Wade,[10] who obtained the volt—time characteristics of breakdown of certain suspension and pin-type insulators. For these results the start of the wave was used as the time reference point, instead of where the voltage exceeded the steady-state breakdown value. The flashover was taken as the point where the abrupt drop in voltage occurred.

Torok and Ramberg,[11] in work of a different nature, used the 60-cycle crest breakdown value as a reference. Thus, there appears to be some disagreement as to the start or initial reference point of the breakdown. Although this difference is negligible in the case of long time lags, it might readily cause a large discrepancy when the breakdown time becomes very short. It appears, then, that some other factor must be formed which will establish more definitely an initial time reference point.

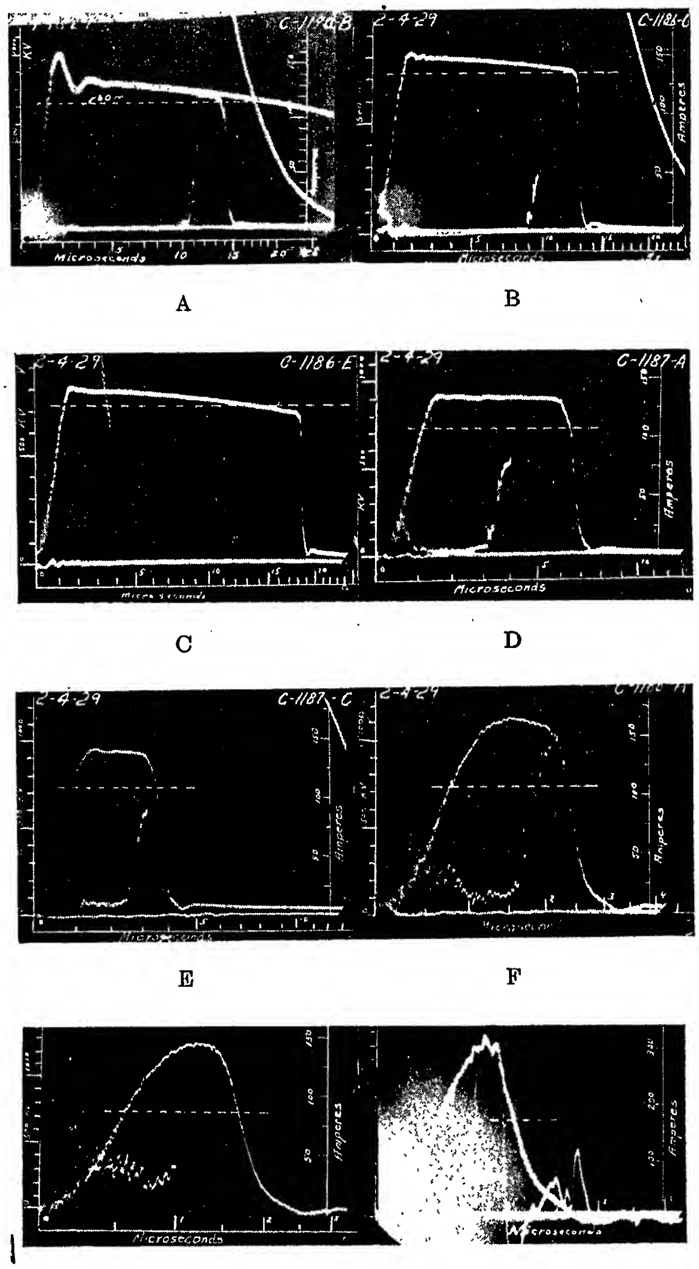
Currents Preliminary to Breakdown

The magnitude of currents prior to breakdown as shown by Slepian and Torok was determined by sphere-gap measurements, and consequently only the crest values of the currents drawn by the streamers were obtained. Although this determination was far from complete quantitatively, since only the approximate form and the magnitude of the applied waves were known, it served to indicate the definiteness of extensive preliminary ionization. This ionization is of vital importance from the standpoint of insulation research and application, since it introduces a new consideration which may help to solve some of the mysteries of the performance of insulation.

Additional Streamer Current Work

The rapid development and application of the cathode ray oscillograph have made possible a more complete study of these preliminary currents. A special adaptation of the oscillograph was necessary in this work, however, since a practically perfect reproduction of phenomena was essential to obtain both current and voltage traces accurately upon the same film. In this application linear coordinates and a single sweep of the cathode ray across the film were considered most desirable. This required a method of synchronization whereby the cathode ray beam, a timing system, and the test potential were under close control. The final arrangement permitted the whole sequence to be repeated at will with a maximum time variation of one fifth of a microsecond. Fig. 1(a), in which two successive traces superimpose upon each other, and Fig. 3(c) in which five applications at different voltages are recorded, show how closely synchronism may be obtained. Thus, a single oscillograph was employed, and the two traces, which represent current and voltage, were secured by consecutive voltage applications. It is fully realized that a two-element oscillograph, which at the present time would mean two separate cathode ray oscillographs, would meet the requirements of this application much better than a single instrument, and work is under way in this direction. In the present case a slight variation of voltage on consecutive applications might appreciably change the magnitude of the resulting current; this possible error in the current was partially eliminated by averaging results from several oscillograms of each test condition.

The test procedure used to obtain time-lag oscillograms was in general the same for all tests. The voltage of the surge generator was regulated to a critical value barely sufficient to flash over the insulation. Several oscillograms were then obtained at this setting, after which the surge-generator voltage was slightly raised, and more oscillograms were taken. This procedure was continued until the voltage limit of the generator was reached. The voltage was reduced by a potentiometer and transmitted to the oscillograph through a cable to obtain the volt—time traces. Current was determined from the drop across a series resistor, and this drop was also transmitted to the oscillograph through a cable. The latter cable was protected against overvoltage by a small sphere-gap adjusted to break down on excessive currents.



A B C D E F G H

Fig. 1—Cathode Ray Oscillograms of Flashovers on Four Pillar Type Insulators

A The accuracy of the timing arrangement is shown by the manner in which successive voltage waves coincide perfectly up to the point where one resulted in flashover

B Current and voltage relations. Note the abrupt rise of the ionization current

C Completion of the flashover after the voltage dropped below the 60-cycle crest flashover value

D A marked reduction in time lag produced by a higher applied voltage

E The effect of further increasing the voltage is shown

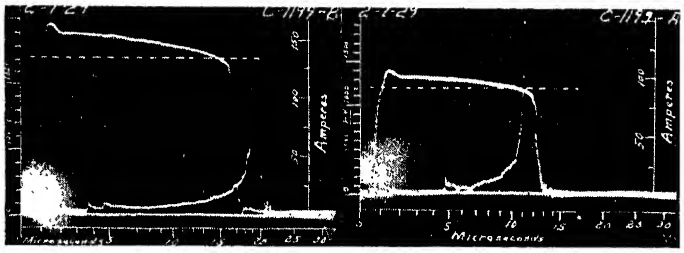
F The streamer currents may be prominent before the crest of the wave is reached

G The phenomenon of F is more apparent here

H Streamer currents limit the maximum voltage reached

Discussion of Oscillograms

The current drawn by the apparatus under test is the resultant of two distinct components, the charging current and the ionic current. These may be segregated by first determining the charging current from the recorded voltage wave and the capacity of the apparatus and graphically subtracting this current from the total. Unfortunately the majority of the apparatus tested and discussed herein has capacity sufficiently high to draw charging currents of 25 to 75 amperes, thus making the determination of small ionic currents unreliable during the charging period. Another method of obtaining the point at which extensive ionization occurs is to impress a flat-topped wave of such a magnitude that ionic currents start only after the charging period is over. Identical results from these two methods cannot be expected, as the difference in the time involved is quite large. In one case appreciable streamer currents must develop in a few hundredths of a microsecond, whereas with the other method the time for development is limited only by the ability of the generator to maintain the voltage.



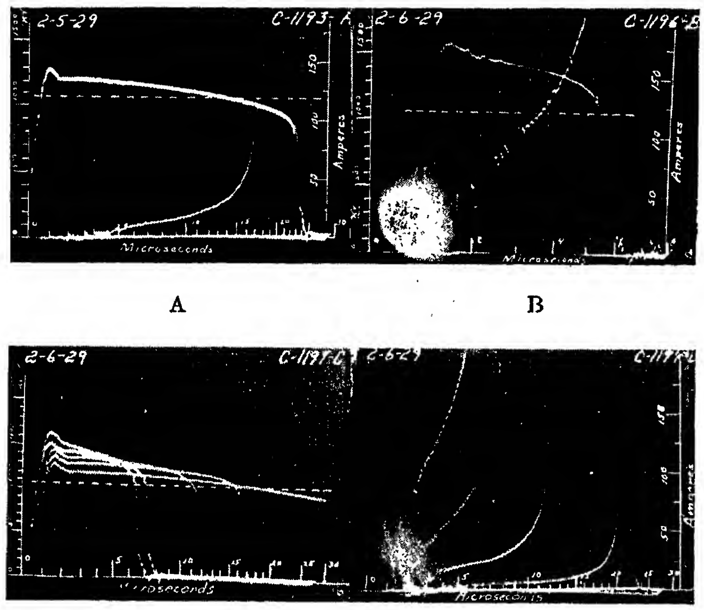
A B

Fig. 2—Surge Flashovers of 16 Suspension Insulators

A Voltage and current relations
B Note the sudden rise and fall of current previous to the normal increase

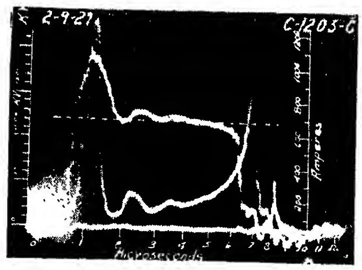
A close examination of the oscillograms depicting long time lags on pillar type insulators, as in Fig. 1(b), shows the abrupt start of the ionization current. This takes place after an interval of time which depends upon the amount of overvoltage above a critical value, below which ionization currents of appreciable magnitude cannot be obtained. Fig. 1(c) shows a flashover which was completed after the voltage had fallen below the 60-cycle breakdown value. This may be explained by the slow rate of formation of space charges and small streamers when the voltage barely exceeded the 60-cycle value. The formation of streamers decreased the effective spacing between the electrodes; this, together with the needle-gap properties of the streamers, raised the gradient to a value sufficient for the completion of breakdown. This point is substantiated by oscillograms on other apparatus, which follow. A slight increase in the applied voltage produces a marked reduction in time lag, as shown in Figs. 1(d) and 1(e). In Fig. 1(g) the streamer currents were very prominent even before the crest of the wave was reached. Fig. 1(g) shows this effect amplified still further, while in Fig. 1(h) the streamer currents were so large that the voltage wave was limited to 1350 kv. instead of reaching the voltage of the generator, which was 2000 kv.

Tests on a string of 16 suspension insulators showed similar breakdown characteristics, with the exception that at low voltages the current did not rise as abruptly, Fig. 2(a). An interesting phenomenon is shown in Fig. 2(b), where the current remained very low for several microseconds after the voltage reached its crest; then an abrupt rise and fall occurred, after which



A B

C D



E

Fig. 3—Surge Flashovers on a 16-Unit Insulator String Equipped with Arcing Rings of Four-Inch Diameter Pipe

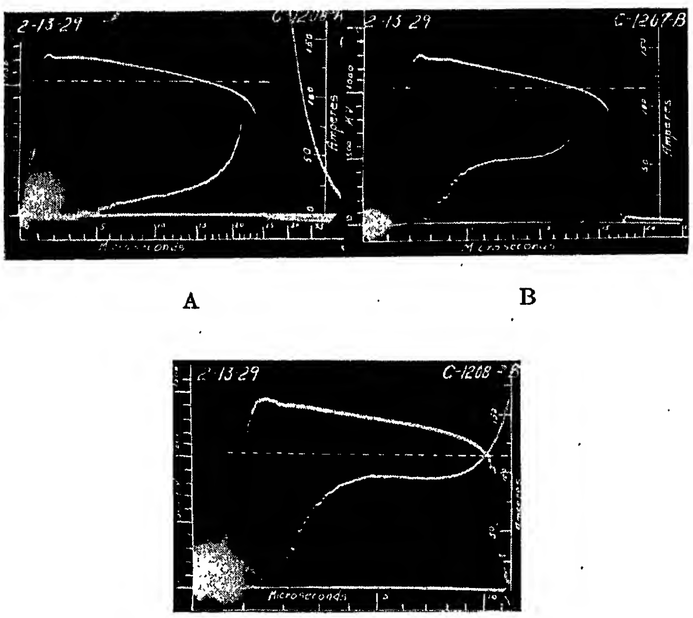
A Voltage and current relations
B The effect of increasing the voltage is shown
C Five successive applications at increasing voltage. The inverse relation between overvoltage and time lag is well illustrated
D The currents corresponding to (C)
E The response of the current to potential variation is shown

the current increased in a normal manner. It is probable that streamers were initiated at the time indicated by the first sudden rise in the current.

Insulator strings equipped with arcing rings behave somewhat differently from plain strings, under surge voltages. The nature of the arcing rings seems to determine almost entirely the resulting characteristics. Fig. 3(a) is an oscillogram of a flashover on a 16-unit

string of insulators equipped with two arcing rings of four-inch pipe. Fig. 3(b) shows the corresponding current and voltage waves with moderate overvoltages. The start of the current wave was modified by high-frequency oscillations, (20,000 kilocycles), which were probably initiated by small rapidly forming streamers and thereafter maintained by leads which could not easily be eliminated. The effect of variation of the applied voltage is shown in Fig. 3(c) where flashover occurred in all but one case. The corresponding currents appear in Fig. 3(d).

Arcing rings of the strap type have somewhat different characteristics. Figs. 4(a), 4(b), and 4(c) are typical oscillograms of the voltage and current waves. The flat portions of the current waves probably were caused by the decreasing voltage waves. In Fig. 3(e), the voltage increased to a high value and then dropped to the 60-cycle flashover value. The large change in current caused by a relatively small potential variation shows clearly that the rate of ionization depends upon the overvoltage above a critical value. It also follows that the rate of ionization depends upon the nature of the stress distribution throughout the field.



A B C

Fig. 4—Surge Flashovers on 16 Suspension Insulator Units Equipped with Circular Arcing Rings of ¼-In. Strap

A Current and voltage relations with a slight overvoltage
B Current and voltage relations with a moderate overvoltage
C Current and voltage relations with a still higher overvoltage

In the breakdown of insulation, particularly of the gaseous form, ionization does not start at the time of the sudden reduction in voltage. The process may start 25 or 30 microseconds prior to the instant when the gas becomes highly conducting. In full consideration of this fact such terms as time lag and breakdown time become indefinite and arbitrary unless they are defined very completely. The rate of increase of current near the completion of flashover is so great that the voltage is abruptly reduced to a negligible value in a fraction of a microsecond. Thus for breakdowns where the voltage remains at a high value for considerable time, that is, with long time lags, variations in the determination of the breakdown point will be small in comparison. On the other hand, when breakdown occurs in a short time, as in Fig. 1(g), these variations in the arbitrary points of the start of breakdown and the time of completion are such a large part of the surge duration that the results of different interpretations may deviate as much as 200 per cent.

Attenuation

Klydonograph data obtained on transmission lines have shown that high-voltage surges which have caused flashover at some point of the line attenuate much more rapidly than low-voltage surges. This high rate of energy dissipation at high voltages commonly is attributed to corona on the line. However, with a chopped wave, which results when the line insulation breaks down on the front of a high overvoltage wave, streamers will form on the succeeding insulators and thereby produce high currents which will reduce the voltage much more rapidly than is possible with corona alone. The space charge and streamers that exist when the current is large, invariably result in flashover, unless the tail of the wave is abrupt or chopped.

Conclusions

1. The process of breakdown of insulation on surge voltages does not start until the steady voltage breakdown value has been exceeded. Hence, it seems logical to compute time lag of breakdown from the first crossing of the steady breakdown value by the voltage wave instead of from the beginning of the wave.

2. After breakdown has started, ionization or streamer currents increase in magnitude, as the streamers develop between the electrodes, until the gap is spanned, when the current limit is determined by the generator characteristics.

3. The magnitude of the streamer current at any time apparently is a function of the amount of overvoltage above a critical value.

4. Streamer currents are indicative of an unstable condition and therefore cannot be used for protective purposes except against chopped waves.

5. Streamer currents cause faster attenuation of high-voltage chopped waves than can be attributed to corona alone.

6. The rate and amount of energy dissipation prior to complete breakdown between two electrodes is a function of the nature of the electrostatic field.

7. Terms such as time lag, sparking time, and breakdown time are vague unless they are very completely

defined. The time lag (as defined in this paper) of commercial apparatus values from 10^{-7} to 10^{-4} seconds.

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Discussion

K. B. McEachron: The results of this paper indicate that it is not sufficient merely to test an insulator with a voltage rising at a certain rate but the generator must be capable of supplying sufficient current so that the rate of building up of the streamer currents is not limited by the capability of the impulse generator. I believe that the generators used in the past for determining insulation flashover have been in most cases designed liberally from the standpoint of current. For instance, the 5,000,000-volt generator at Pittsfield is capable of delivering many thousands of amperes during the discharge over an insulator string.

It seems to me however, that some test should be made on insulator strings on transmission lines with the impulse traveling several miles since the surge impedance of the line imposes a limitation on the amount of current available for the formation of streamer currents. It would be interesting if the authors could tell us how the streamer currents compare for one insulator and 16 insulators with the same proportional transient voltage supplied. It may be that only at the lower potentials and with short strings would the surge impedance of the transmission line delay the formation of the streamer currents.

Under the heading of "Attenuation" the authors state that when an insulator flashover chops the traveling wave on a transmission line, the high rate of attenuation is due largely to the formation of streamer currents on succeeding insulators. Tests in Michigan with artificial lightning on transmission line conductors indicate that a wave chopped by a sphere-gap much below the insulator flashover value still attenuates more rapidly than does the full wave of the same potential.

Since streamer currents are required between spheres or other points of opposite potential before actual breakdown occurs, it is reasonable to suppose that the conductors themselves develop streamer currents and that to establish corona considerable starting current must flow, which seems to be the more reasonable explanation of the greater attenuation of chopped waves than of full waves. I should like to compliment the authors on the excellent oscillograph work in this paper although the reproduction makes the study of some of these oscillograms difficult.

J. T. Tykociner: The investigations described in this paper throw valuable light on the phenomena of breakdown in gases. As in former experiments the existence of large currents preceding the complete breakdown was found in accordance with Doctor Slepian's theory. In view of these results, who can deny that we possess in the cathode ray oscillograph a powerful instrument of research. We tend, however, to become overenthusiastic as to the possible information we may expect from the cathode ray oscillograph. We must take into consideration that the oscillograms reveal total discharge currents as function of time and voltage. They do not disclose all the information required for the construction of a complete picture of the mechanism of breakdown. We need in addition to these oscillograms knowledge of the distribution of current density and potential along and across the path of breakdown. We can hardly hope that the present-day oscillograph may serve in connection with the determination of electron or ion density distribution. It seems that, in addition to the theory of thermal ionization, we will also have to borrow from astrophysicists the instrument they are using in the study of the radiation emitted by the sun and stars, an instrument older and simpler than the cathode ray oscillograph. I have in mind the spectroscope. The spectra revealed by spectroscope also present oscillograms, but of another type. They indicate the highest frequencies produced in discharges by atoms and molecules in state of excitation. The existence of strong electric fields in an electric discharge is evidenced by splitting and widening of spectral lines and bands. The phenomenon is known as Stark effect. It should also be possible to determine the density of current from point to point all over the area of discharge by making use of the Zeeman effect. Measuring thus the position, width, and intensity of spectral lines may lead to a precise knowledge of the distribution of electric and magnetic fields for all regions and phases of breakdown in gases. The distribution of temperature can be measured by thermopiles subjected to the radiations emitted by different parts of the discharge. The short intervals of time at which a given spectrum will have to be photographed may be controlled by a Kerr cell. Physics, especially astrophysics, has ready for us the methods of investigation. I wish to suggest that the time has come for engineers to apply these powerful means for high-voltage research.

R. H. George: There are two questions having to do with discharge phenomena with short gaps which I should like to ask Mr. Torok in connection with this excellent paper.

Did changing the polarity of the electrodes make any difference in the breakdown potential of the gaps, or was this tried? Some investigations conducted by K. A. Oplinger and the writer[1] some years ago on the d-c. breakdown of point-to-plane gaps, showed the breakdown potential to be very much higher with the point negative than with it positive.

Was any reduction in the time lag found with insulators illuminated with ultra-violet light as compared with ordinary laboratory illumination and total darkness? I assume the curves represent an average value of time lag, and I should be interested to know something of the variation found in the lag.

S. C. Sprague: I had always understood that a string of insulators might be assumed to approximate a needle-gap and that the time lag of such a gap was variable and quite subject to humidity and other atmospheric conditions. I suppose those several oscillograms were taken all within a very short time of each other and that that is is how they were able to check the theory so well.

J. J. Torok: From his first question it appears that Mr. McEachron thought we had tried to attribute all the losses on the line to streamer currents. We did not mean that at all. There is certainly a great deal of energy dissipated through corona. We have done a considerable amount of work on corona and have determined the amount of loss at different voltages. The losses in the formation of streamer currents, however, only appear when the voltage exceeds the steady-state breakdown value of the insulator so we may say this: That the line dissipates a great amount of energy due to corona but at voltages above the breakdown value of the insulators we get a still greater draw of current and consequently a greater loss. For this reason it is not pos-

1. Bulletin No. 19, Purdue University Engineering Experiment Station, Lafayette, Ind. "A Photographic Study of High-Voltage Discharges," by R. H. George, Karl B. McEachron, and K. A. Oplinger, 1925.

sible to send an unlimited current into the substation. The currents due to traveling surges will be modified within the station by the energy dissipation in corona as well as about the insulators on the line.

Professor Tykociner has made a very valuable and interesting suggestion. This would make it feasible to measure the currents at any point within the gap without the introduction of electrodes which would distort the original field. It would be very desirable if this scheme of measurements could be set forth in full detail. The synchronization of the Kerr cell as well as the spectroscope may present some difficulty; however, this scheme is of great value because it offers another means of measuring these currents and thus checking the present methods of determination which are exceedingly difficult to make and in which large errors may appear. Unfortunately all of our measurements on streamer currents have been made with one polarity, that is with the negative grounded. Because of the great amount of work to be done on various different problems, measurements using a positive polarity grounded have not been made. It is intended to continue this investigation with reverse polarities.

The question has been raised concerning the effects produced by variations of free ions within the gap. For small gaps illumination of the electrodes by ultra-violet light produces considerable effect. With large gaps this effect becomes almost negligible. In the laboratory, to produce an increase in density in free ions by means of ultra-violet light, a very powerful source is required as the lamp would necessarily have to be placed about 20 ft. away from the apparatus to be tested and the useful energy would not be very large. We have done some work of this nature in which we used sunlight. With large gaps having spacings greater than 5 cm., the effect of the increased ionization became negligible. Repetition of this test with insulators showed that the effect of ultra-violet light was nil. The application of ultra-violet light did not alter the random element in the phenomena of breakdown when large gaps were used. The variations of time in breakdown under a given voltage remained practically the same.

Because of the variation in breakdown time it is necessary to take many oscillograms at one given voltage to determine a fairly accurate average of the breakdown time; thus instead of making only eight or ten oscillograms to represent a time lag curve it is necessary to obtain 40 or 50.

Mr. Sprague spoke of the variation in results produced by changing humidity. We have not encountered much difficulty from that score as most of the tests were made within a period of time less than four hours; however, we have noticed slight variations in characteristics from day to day but this effect has been so small that it may be entirely neglected.

Dissipation of Heat by Radiation

BY A. D. MOORE[1]

Member, A. I. E. E.

Synopsis.—Heat dissipation is an ever-present factor affecting the design and operation of many kinds of electrical equipment. Usually, the problem is to get rid of heat due to losses. Sometimes the problem is how to conserve heat. Radiation, or convection, or conduction, or combinations of these, enter into all cases. Engineering literature as a rule presents conduction and convection in sound terms, but in many cases, the treatment of radiation is unsound, misleading, and sometimes in error. This paper is presented with the hope of putting heat radiation in engineering applications on a sounder basis.

The usual laws given to cover total heat radiation are stated and discussed, and their limitations brought out. Net heat loss by radiation interchange for the cases of parallel and concentric surfaces are reviewed and stated.

The problem of total radiation from a rectangular slot is attacked, the method of solution is indicated by example and discussion, and the results given.

Section I

INTRODUCTION

THE term "radiation" has been so thoroughly corrupted by being used to include all forms of heat dissipation, that it needs definition at the outset. Radiation, within this paper, does not include heat dissipation by convection, either natural or forced. It applies only to true radiation, either emitted, reflected, or absorbed by a surface. Radiant heat energy covers the range of the spectrum, including the visible, or light wave energy. Heat waves behave as the more commonly known light waves behave,—they are electromagnetic waves traveling in straight lines; they are reflected by mirror surfaces as light is reflected; a given surface emits, reflects, or absorbs to varying degrees, depending on the character of the surface.

STEFAN'S LAW OF EMISSION

Stefan formulated the law of radiation emission,

$$R = k\,e\,T^4$$

where R is the rate of heat radiation emission from a unit of surface, e is the emission coefficient for the surface, k is a constant, and T is the temperature in degrees Kelvin (absolute) of the surface.

Stefan-Boltzmann Law. When a radiating body is subject to reception of radiation from surrounding radiating bodies, as is usually the case, there is an interchange. The net loss of heat from the body by radiation interchange is perhaps most commonly given in engineering literature in the form of the Stefan-Boltzmann Law,

$$R = S\,k\,e\,(T_1^4 - T_2^4)$$

in which R represents the net rate of losing heat by the body; S is its surface; k is a constant; e is the emission coefficient for the surface; T_1 is the temperature (Kelvin) of the surface; and T_2 is variously and loosely described.

Let Fig. 1 represent the body, which has an irregular surface. When the above formula is given, it is usually not stated whether S is to be the actual surface, or the enveloping surface. Usually, nothing is said as to why the surface of the surrounding bodies, and their emission coefficient, are omitted. And T_2, depending on the writer, is given as being

1. Temperature of surrounding walls
2. Temperature of surrounding air
3. Temperature of surrounding objects
4. Temperature of surrounding space.

In succeeding articles in this section, an attempt will be made to place radiation interchange, in simple cases, on a more definite basis.

Black-Body Radiation. At a given temperature a black-body surface radiates more than any other surface. It radiates the maximum possible amount in all

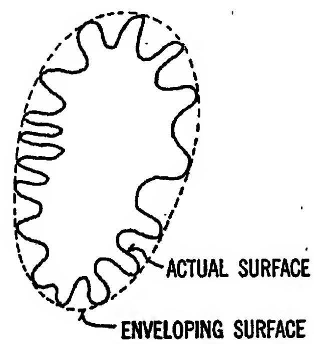

FIG. 1

wavelengths, although the energy is distributed over the various wavelengths according to a familiar curve. The black-body is the standard of reference, and its total emission coefficient, e, is herein taken as unity. When energy falls on a black-body, none is reflected Hence, a small window opening into a large black-lined cavity, being a nearly perfect energy trap, is a nearly perfect equivalent of a black-body surface.

SELECTIVE RADIATION

A given surface may emit selectively; in some wavelengths it may emit (radiate) as much energy as does a black-body, in others, less, and in some, none.

GRAY-BODY RADIATION

If a surface emits so that the energy of all wavelengths is reduced by the same per cent below that which is

1. Associate Professor of Electrical Engineering, University of Michigan, Ann Arbor, Mich.

Presented at the Great Lakes District Meeting of the A. I. E. E., Chicago, Ill., Dec. 2-4, 1929.

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emitted by a black-body at the same temperature, it is called a gray-body. For example, if its total coefficient is 0.7, it emits seven-tenths as much energy in every wavelength as does the black-body. *In this paper, only black-body and gray-body radiation will be dealt with.* Further, only opaque surfaces will be considered.

Absorption and Reflection

The absorption ability of a surface depends upon its ability to emit. If it can emit in a given wavelength, it can absorb that wavelength. If it emits completely, as a black-body, it absorbs completely. Incomplete emission, as for a gray-body, is accompanied by incomplete absorption for energy falling upon it. With unity as a base, emission and absorption coefficients are equal. Energy not absorbed is reflected (by opaque surfaces), and the reflection coefficient is $(1 - e)$.

Prevost's Law of Exchange

By this proposition, radiation emission goes on irrespective of energy that may be absorbed at the same time.

Stefan's Law Written to Give Watts

Stefan's law of emission is

$$R = S\, e\, 36.9 \left(\frac{T}{1000}\right)^4$$

where R is watts, S is the surface in square inches, e is based on unity, and the constant is as given.

It is important to note that this law gives initial emission correctly only if the surface is so disposed that none of it receives radiation from some other part of it, and that it gives only emission; it takes no account of radiation received from other possible bodies in the neighborhood.

Net Radiation Transfer of Heat for Simple Interchange Cases[2]

(*a*) *Parallel Surfaces.* Two parallel surfaces, of the same extent, are placed so close together that escape from edge openings is negligible. S_1 has e_1 and T_1 for emission coefficient and temperature, respectively, and for S_2, like quantitites are e_2 and T_2. The two energies initially emitted by the two surfaces in a given time increment, are inter-reflected, with two infinite series as the result. The net watts lost by S_1 will be

$$R = 36.9\,(1000)^{-4}\, S_1\,(T_1^4 - T_2^4)\,\frac{e_1\, e_2}{e_1 + e_2 - e_1\, e_2}$$

(*b*) *Concentric Spheres.* Let S_1, e_1, and T_1 be the surface in square inches, the coefficient, and the temperature, respectively, for the surface of an enclosed sphere, and S_2, e_2, and T_2 like values for the surface of an enclosing spherical wall concentric with the sphere. The net rate of heat loss by S_1, in watts, is

$$E = 36.9\,(1000)^{-4}\,(T_1^4\, S_1 - T_2^4\, S_2\, P)\,\frac{e_1\, e_2}{e_1 P + e_2 - e_1 e_2 P}$$

where P is as follows: at any given stage of reflection, when a quantity of heat H leaves the walls, the fraction P is such that $P\,H$ is the part of H that strikes the enclosed sphere. P is determined by the characteristic of the surface, as to what degree heat coming from it is diffused. If we deal with mat surfaces (as described in Section II), the above expression simplifies to

$$R = 36.9(1000)^{-4} S_1 (T_1^4 - T_2^4)\,\frac{e_1\, e_2}{e_1 \dfrac{S_1}{S_2} + e_2 - e_1\, e_2 \dfrac{S_1}{S_2}}$$

(*c*) *Concentric Cylinders.* This case, as to symbols and treatment, is similar to the preceding case; and with similar meanings, and mat surfaces, the expression for the watts lost by the enclosed cylinder is the same as the final expression given above.

If, in the concentric cases, the two radii are allowed to approach equality, the cases approach the case of parallel surfaces, physically; and the expression for the concentric cases then degenerates into the expression for parallel surfaces, as it should.

Again, in the concentric cases, if S_2 becomes infinite so that the enclosed body is a very small object in a very large room; or if, with finite dimensions, the coefficient e_2 of the enclosing wall is made unity (black-body), the expression degenerates into the Stefan-Boltzmann law. Thus the Stefan-Boltzmann law is correct only under one or the other of the two conditions specified at the beginning of this paragraph.

Section II

THE SLOT

Convolutions

When a body is corrugated, like a transformer tank, or when it is slotted, or when cooling fins are attached to it,—is its radiating ability increased, or is its radiation, effectively, determined by its enveloping surface? Probably the simplest ideal set-up for answering this question is to compare the total radiation of a slot with the radiation from an undisturbed portion of surface that would just cover the slot mouth.

The Mat Surface

Underlying the development of the concentric cases of Section I, and all of the work in this section, is the assumption of the mat surface. The mat surface is a diffusing surface, both for radiation it may emit, or for that which it may reflect. It obeys the cosine law. Imagine a small increment of such a surface, and erect on its plane a hemisphere with the area at its center. Radiation from the area is most intense through the spherical shell along the normal radius; call this intensity, I. Then the intensity at the shell for any other radius is $I \cos\theta$, where θ is the angle between the selected radius and the normal radius. This is

2. The full development for the cases is given in "Fundamentals of Electrical Design," A. D. Moore, McGraw-Hill.

equivalent to saying that for the mat surface, the intensity in watts per square inch at the point of view is proportional to the projected area as viewed from that position, all positions being at the same radius.

The Slot

The paper from here on is concerned with finding the total radiation per unit length from a rectangular slot that is infinitely long, 2 in. wide, and 8 in. deep. The solution method is semi-mathematical. The entire slot surface is divided into strips of equal width (1 in.), and accurate "interchange" values are found mathematically.

Fig. 2 shows the slot. Let the strip shown as Level 1 emit uniformly 100 watts per sq. in. Then, by simple mathematical processes not given here, the values to the left of the slot were found. For example, the top

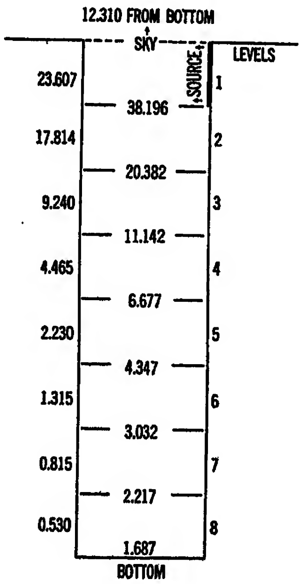

Fig. 2

value is 23.607, which means that of the 100 watts sent out by the right strip, Level 1, the opposite or left strip, Level 1, receives 23.607 watts; and strips at other levels receive less amounts. From these values it is a simple matter of argument and arithmetic to obtain all other values given in Fig. 2.

For example, the figure shows that if a floor were placed 1 in. down the slot, it would receive, out of 100 watts leaving Level 1 strip (at one side only) 38.196 watts; and the true bottom would receive 1.678, as shown.

Principle of Reciprocity

Suppose a surface of any size, S_1, being a uniformly dense source of 100 watts per unit area, sends a total of W watts to another surface of any size, S_2. Then if S_2 is made a uniformly dense source of 100 watts per unit area, it will send the same, or W, watts, to S_1. This principle is too well known to prove here, and anyone unfamiliar with it can easily verify it by study of simple cases.

This principle at once gives a double meaning to every value shown on Fig. 2. For example, the interchange value connecting a strip in Level 1, and the entire bottom, which is two strips wide, is 1.687, the meaning of which, in one direction, was given above. In reverse, or by reciprocity, if the bottom is a uniform source of 100 watts per sq. in., it will send to the strip in Level 1, 1.687 watts per sq. in.

Fig. 2 thus gives interchange values between any wall strip and any strip in the opposite wall, and between any wall strip and the bottom. It also gives 12.310 as the interchange between bottom and sky opening, a value easily obtained once the other values were established. All values given on Fig. 2 are, it is believed, correct to one-tenth of one per cent.

Method of Attack

It is possible, by assuming the slot surface to be at such a temperature as to cause it to be a uniform density source of 100 watts per sq. in., to proceed with the different stages of reflection and eventually, to find the total emission from the slot mouth. Instead, the same result will be found in a different way. A uniform "sky" is placed over the slot mouth, which uniformly sends 100 watts per sq. in. of slot mouth into the slot; and the energy total finding its way out again is determined. From the two values, the result desired can be computed.

A basic set of figures is obtained by using a coefficient e of zero, reflection then being total. Initial reception by different levels on one side, and reception per unit on the bottom, for each 100 watts admitted from sky by the slot opening, are given in Table I.

TABLE I
INITIAL RECEPTIONS FROM SKY

Level	Received from sky	
1	38.196	
2	20.382	
3	11.142	
4	6.677	
5	4.347	
6	3.032	
7	2.217	
8	1.687	
	87.680	
Bottom	12.310	
	99.990	checks 100

First Stage

The set of figures showing a quantity of energy sent out by reflection, and being received or allowed to escape, or both, will be called a stage. Stage 1 is given in Table II. The first two columns of Table II give the figures on the eight levels in the side wall. Level 1 being typical, its group of values will be discussed. At the head of the group is 38.196, the watts received by a strip in Level 1 from the sky. e being zero, and $(1 - e)$ being unity, all this energy is reflected; its

reception by the opposite wall strips is shown by the first of the figures in each of the groups of eight sets of figures for the eight levels. For example, out of 38.196, there is sent to Level 1, 9.02; to Level 2, 6.81; and so on. These two values were obtained by multiplying 38.196 by the proper interchange values, 23.607/100 and 17.814/100, as taken from Fig. 2.

In the group of figures for any level, the values are, in order from the top down, that level's reception from the eight levels, taken from top down. Addition of a group gives total reception by a strip in a level from the complete opposite wall.

TABLE II
STAGE 1

	38.196		4.347	E. S.
Level 1	9.02 3.63 1.03 0.30 0.10 0.04 0.01 0.01	Level 5	0.85 0.91 1.03 1.19 1.02 0.54 0.20 0.07	14.60 4.15 1.24 0.44 0.19 0.09 0.05 0.03
	14.14		5.81	20.79
	20.382		3.032	E. B.
Level 2	6.81 4.82 1.98 0.62 0.19 0.07 0.03 0.01	Level 6	0.50 0.45 0.45 0.62 0.78 0.72 0.39 0.16	0.644 0.452 0.338 0.290 0.290 0.338 0.452 0.644
	14.49		4.07	3.45
	11.142		2.217	Check
Level 3	3.53 3.63 2.64 1.19 0.40 0.13 0.05 0.02	Level 7	0.31 0.27 0.25 0.30 0.40 0.54 0.52 0.30	14.14 14.49 11.59 8.34 5.81 4.07 2.89 1.93
	11.59		2.89	63.46 20.79 E. S. 3.45 E. B.
	6.677		1.687	87.70
Level 4	1.71 1.88 1.98 1.57 0.78 0.28 0.10 0.04	Level 8	0.20 0.166 0.146 0.149 0.194 0.28 0.395 0.40	which checks 87.68 from Table I.
	8.34		1.93	

By appropriate use of other interchange values given in Fig. 2, the "escapes" of energy coming from the wall, to sky and to bottom, are computed. These are shown, Table II, under E. S. (Escape to sky) and E. B. (Escape to bottom).

As an indispensable check, the CHECK column is made out. It shows, for this stage, total reception by the eight levels, and the sum of this, and the two escapes. This total must closely check with the energy initiating this stage, which is 87.68, taken from Table I.

The level receptions, eight in number and totaling 63.46, are now used to initiate Stage 2, where computations are carried out precisely as in Stage 1.

Note that energy falling on the bottom is left there in Stage 1 and succeeding stages like it. This energy will be treated later.

SELF-REPEATING DISTRIBUTION, AND SUMMATION

Eight stages were carried out, seven of which are not given here. For the end of Stage 8, the reception values for the eight levels closely approached symmetry.

In any closure, successive reflections achieve more and more closely a distribution which is self-repeating in form; it will not be self-repeating in size unless there is no absorption and no escape. This proposition has not been given general proof, but in all cases worked on by the writer, it has been entirely evident that the proposition has governed the later distributions. The distribution approached is symmetrical only if the enclosure is symmetrical. In the present case, the enclosure is symmetrical, since it consists of walls only, bottom for the moment being treated as not reflecting.

Receptions at the end of Stage 8, for eight levels in order, are given in the first column, Table III. In the next column the total of the first column is re-distributed so as to give a self-repeating distribution. The re-distribution was done by trial and error, only two trys being necessary to get the accuracy shown. Stage 9 consisted of beginning with the values as re-distributed, and finding the receptions of the fourth column. Column 5 shows that every level repeated its energy value by a factor closely approximating to 0.838, the Repeat Factor for the present enclosure of walls only.

TABLE III

Level	Actual receptions at end of stage 8	Preceding values re-distributed to give self-repeat. distribution	Receptions at end of stage 9	Repeat factors
1	1.27	1.21	1.01	0.835
2	1.73	1.68	1.41	0.839
3	2.07	2.02	1.70	0.842
4	2.21	2.20	1.84	0.837
5	2.18	2.20	1.84	0.837
6	1.97	2.02	1.70	0.842
7	1.63	1.68	1.41	0.839
8	1.18	1.21	1.01	0.835
Escape to sky or to bottom................			1.375	
Average repeat factor......................				0.838

From here on no more stages are needed, as all terms beyond the self-repeating stage can be handled by summing up an infinite series.

Table IV lists all escapes for an over-all check. Escapes to sky and bottom for the first eight stages are given. For the ninth and succeeding stages, the infinite

series comes in. The repeat factor, 0.838, operates on escapes as well as on side-wall distributions, so that escapes to sky, for instance, would be that occurring in Stage 9, plus another reduced by 0.838, etc., as,

$$1.375\,(1 - 0.838 - 0.838^2 - 0.838^3 - \ldots)$$

$$= \frac{1.375}{1 - 0.838} = 8.50$$

The sum of all escapes should total 100, as all values have been taken on the basis of 100 original watts entering from the sky, and there has been no absorption. The sum obtained, 103.05, checks satisfactorily, considering all the steps through which reflections have been carried.

Procedure for Coefficient Other than Zero

Table V carries out the steps required when the emission coefficient is 0.1, reflection coefficient then being 0.9. The first column contains the reflection coefficient raised to a power equal to the number of the stage. The second and fourth columns are copied, for eight stages, from Table IV. Values of the first column are multiplied into the values in the second and fourth, to give the third and fifth columns. An exception is to be noted for the first escape to bottom, which, having come direct from sky, is unmodified.

TABLE IV
ESCAPES

Stage	E. S.	E. B.
		12.31
1	20.79	3.44
2	10.63	3.39
3	6.77	3.30
4	4.74	2.97
5	3.55	2.65
6	2.76	2.28
7	2.17	1.92
8	1.74	1.62
$\frac{1.375}{1 - 0.838}$ =	$\frac{8.50}{60.65}$	8.50
		42.40
		60.65
		103.05

TABLE V

	E. S.		E. S.	
$(1 - e)^n$	$e = 0$	$e = 0.1$	$e = 0$	$e = 0.1$
			12.31	12.31
0.9	20.79	18.70	3.44	3.23
0.81	10.63	8.61	3.39	2.75
0.729	6.77	4.94	3.30	2.41
0.656	4.74	3.11	2.97	1.95
0.59	3.55	2.10	2.65	1.56
0.532	2.76	1.47	2.28	1.21
0.479	2.17	1.04	1.92	0.92
0.431	1.74	0.75	1.62	0.70
0.388	1.375			
$\frac{0.388 \times 1.375}{1 - 0.838 \times 0.9}$ =		2.18		2.18
		42.90		29.22

The escapes for Stage 9 are reduced to (0.388×1.375). Instead of summing up the infinite series by dividing this value by $(1 - 0.838)$, it must be divided by $(1 - 0.838 \times 0.9)$, or $(1 - 0.755)$. This is because successive escapes are now reduced not only by the Repeat Factor, but also by the absorption of 0.1. Total escape to sky is 42.90, and to bottom 29.22.

The energy escaping to the bottom, and its effects, must now be taken care of. The bottom will now be considered as a source the same as the sky was. Its position bears the same relation to the walls and sky, in reverse, as the sky did to the walls and bottom. Therefore, just what the sky did, in toto, must be determined.

The sky admitted 100 watts, and due to inter-reflection by *walls alone*, got back (by escape to it) 42.90. The bottom, due to escape values "saved up" there, is now a source of 0.9×29.22. But this source, being like a sky source, gets back 42.90 parts in a hundred, or $0.429\,(0.9 \times 29.22)$. Of this, 0.9 will be sent out again,

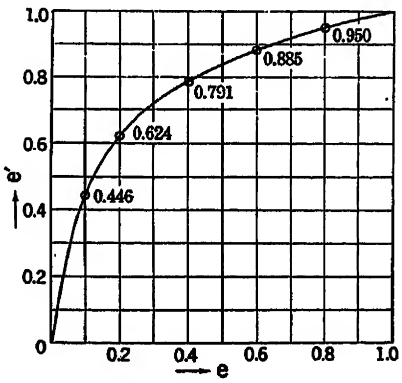

Fig. 3

and some will return, and so on. The total value of the bottom as a source is then, after summing up,

$$0.9\;\frac{29.22}{1 - 0.9 \times 0.429}$$

But what is wanted is the total escape to the sky. If the sky, out of 100, gave an escape of 29.22 to the bottom, the bottom as a source will do likewise for the sky, so the escape to sky due to bottom as source is the above value multiplied by 0.2922, which gives 12.52.

The total escape to sky is then 12.52 plus 42.90, or 55.42, out of 100 originally entering. Or, out of one watt entering the slot mouth, 0.5542 escapes to sky again; this gives a reflection coefficient for the slot mouth. The emission coefficient is $(1 - 0.5542)$ or 0.446. This is called e', the effective emission coefficient for the slot mouth.

Effective Emission Coefficients for Enveloping Surface

In the case just carried through, for an actual e of 0.1, the enveloping surface (slot mouth area) was found to have an effective, e', of 0.446. This means that if a surface of this kind, being originally flat, is improved by putting on fins to make the surface "all slots" of the 2 x 8 size, its total radiation would be increased over

four times, e being 0.1, and surface temperature being everywhere constant.

Fig. 3 shows the relation of e' to e for this slot proportion over the entire range. Ordinates to the curve are believed to have no errors greater than 4 per cent. The points placed in small circles were computed as in the preceding work.

CONCLUSIONS

Stefan's law of emission holds only for non-interfering surfaces. Where corrugations, convolutions, slots, or fins occur, an effective coefficient used in connection with the enveloping surface must be used.

If the surface is a black-body to begin with, radiation is not increased by slotting or finning it; but if e is unavoidably low, considerable benefit may be derived.

It is probable that cooling fins have been added to hot bodies primarily with the idea of increasing dissipation by convection. The above study shows that in a vacuum tube, for example, where convection cooling may be negligible, a hot member made, of necessity, of a metal having a low coefficient, may be considerably assisted in radiating heat by adding fins.

Discussion

Joseph Slepian: The kind of problem which Professor Moore has dealt with here has been put up to me perhaps half a dozen times in my professional career but except for a statement as to the fundamental principles I could not give much satisfaction to my questioners. Now I am pleased to have this paper on hand and know there is a treatment in his book to meet any future occasion when I shall be consulted on this subject.

I recall an experiment which confirms one of the results that Professor Moore has obtained. This experiment was carried out by Mr. Chubb of the Westinghouse Company some years ago with an unexpected result. The particular problem with which Mr. Chubb was concerned was to heat up a fine filament contained in a cylindrical chamber as rapidly as possible. Having made a first test to determine the length of time for the filament to rise to a certain temperature, it was thought that by polishing the inner surface of the cylinder so as to make it strongly reflecting, the time for heating the filament would be shortened. The experiment was carried out and it was found that in the interior of the highly polished cylinder the filament took just as long to heat up as in the unpolished cylinder.

The explanation appears in Professor Moore's paper, where dealing with cylindrical containers, he points out that if the interior body is small compared to the outer body, the nature of the outer wall of the cylinder makes very little difference in the temperature of the inner body. Thus the apparently paradoxical result of Mr. Chubb's is explained.

K. W. Miller: I was under the impression that a slotted surface would not radiate any more heat than the equivalent enveloping area, provided the surface of the material obeys Lambert's law. A piece of porous material at temperature equilibrium in a furnace appears of equal brightness as a smooth surface. If color is an indication of amount of radiation under these circumstances, apparently the porous and smooth surfaces are radiating equal amounts of heat per unit area of enveloping surface at equal temperature. Is there some error in the assumption that a porous body would simulate a slot or is there actually more heat radiated from a porous body?

B. L. Robertson: (communicated after adjournment) Work on heat radiation, as applied to the engineering field, has been rather small, and existing information which can be used in attacking problems involving heat radiation is very meager. The dissipation of heat from electrical apparatus has been previously discussed almost wholly from the standpoint of conduction and convection, and more from convection than from conduction. It seems unnecessary to say that the work of Professor Moore furnishes a welcome contribution to the study of heat dissipation by radiation.

Professor Moore takes the black body as the standard of reference for radiation and uses unity as the coefficient of emission. In other words, his case is ideal, but in that he is perfectly justified. Although an open surface, or the face of a slot, having an emissivity coefficient of one does not actually exist, it can be very closely approached, and to such an extent that the difference is only a few per cent and entirely within practical engineering accuracy. R. H. Heilman has very recently investigated the emissivity values for various surfaces and has found that many materials used in engineering practise have coefficients of emissivity about 98 per cent of that for the black body. This may be another case in which a knowledge of the limitations of certain features of a problem may permit an easier calculated result by allowing simplifying assumptions which could not otherwise be made.

As pointed out in the paper, the temperature T_2 given in the Stefan-Boltzmann law for radiation is a quite uncertain quantity, as is also the area of the radiating surface which is to be used. Most statements concerning the law, and which are found in college textbooks on physics, simply mention *radiation to surroundings*, with no added thought as to the nature of the surroundings, whether or not the surrounding surfaces are the same materials and at the same initial temperatures, or whether or not it makes any difference. One book implies that the law holds only for two black bodies. It is with difficulty that one can thus use the expression to obtain results for even the most simple cases of radiation. The fact that Professor Moore has found the law to hold for only non-interfering surfaces helps to clarify its interpretation to some extent. Certainly, it shows a limitation in its use.

Some time ago a transformer engineer made the statement that the radiation of heat from a plain transformer tank was the same as that from a corrugated tank having the same envelope, and that the radiation was not dependent in any way upon the configuration. The statement was questioned at the time since it is not apparent, but this impression is somewhat generally existent. The paper notes that such a fact is true for only a surface which is initially a black body, and that for surfaces having lower coefficients of emissivity corrugations may appreciably increase the radiation.

Just recently L. Wetherill and J. V. Montsinger have published the results of the effect of the color of the tank on the temperature of self-cooled transformers operating under service conditions. They have agreed with earlier results presented by E. J. Moore and J. H. Moulton which show that transformer tanks painted light gray reduce the oil temperature 1 or 2 deg. cent. more than tanks painted black, but that this difference is in no way pronounced. The conclusions of the first paper indicate that radiation alone for light colored tanks would perhaps show a pronounced effect upon the oil temperature. That is, by conclusion No. 4 of that article it is shown that using very low emissivities a very great increase in temperature rise was found; therefore, first, radiation instead of convection must have been the chief means of dissipation in the tests here referred to, and second, the profound effect seems to show that low emissivities give high, rather than low rises. Any explanation for these results has been omitted from the above treatments, and I should like to ask Professor Moore if, in any of his work, he has come across a reason for this expected reduction not being found.

Montsinger and Wetherill also conclude from test data taken in the field that as the surface of a transformer tank becomes more and more convoluted, the temperature rise for metallic

paints having low coefficients of emissivity becomes less and less. This result agrees directly with the conclusion given by Professor Moore in which he states that if e is unavoidably low, considerable benefit may be derived by slotting or finning a body in order to increase its rate of heat dissipation by radiation.

Lynn Wetherill: (communicated after adjournment) We have done some work on problems of this nature in determining the effect of different kinds of paint on transformer temperatures. It was desired to find the effect of painting a corrugation of 3 in. depth and 2 in. pitch with aluminum (coefficient of emission at operating temperatures about 0.55). A solution similar to that used by Mr. Moore was used except that only three stages were completed instead of eight. At this point it was found that if all the radiation still being reflected were assumed to escape from the corrugation the effective emissivity would be 0.72, while if none of it escaped the effective emissivity would be 0.68. This was considered to give sufficient accuracy. It is interesting to note that the re-entrant portion of the corrugation acted practically like a black body. Only a small amount of time is required to work out such a problem with reasonable accuracy for engineering purposes.

This point illustrates one of the reasons why transformers having a tubular or radiator tank are not much affected by the kind of paint used on the tank, as the effective emissivity is greatly increased by the presence of the convolutions. As a result a paint with comparatively low emissivity will radiate nearly as much heat from a corrugated surface as the customary dark gray paint.

A. D. Moore: If you put a slotted object inside a relatively complete enclosure and bring the whole thing up to a given temperature, one way of knowing that everything is at a uniform temperature is to see that everything disappears in outline. There are certain radiation laws that come into the heat balance situation there and you will know that temperature uniformity has been arrived at when you can't see the slot. However, if you get the object hot enough and quickly take it outside of the furnace (remove it from the black-body enclosure, in other words) and observe it before it has a chance to cool off on the corners, then depending on the reflection coefficient, there is a much greater amount of light from the slot. The thing works backward in terms of light. If you take the slot and imagine it to be a light court in a building in something like the proportions 2 by 8, by lining the cavity with black paint you will get a small amount of direct sky illumination on the bottom windows. If you line the side walls only with an 0.8 reflection paint, the illumination on the bottom windows will go up to something like ten times as much. If you then remember to put in a bottom having an 0.8 reflection value, you will get a total increase of 24 or 25 times as much.

A. D. Moore: Professor Robertson's question about the Wetherill-Montsinger paper (see p. 41) raises an interesting point or two. Since receiving the discussion I have made a number of calculations on temperature rise of transformer temperatures for various conditions.

The gross heat loss of the transformer is (a) its convection loss, or dissipation, and (b) its emitted radiation loss, or dissipation.

The gross heat gain is (c) incident radiation from the sun that is absorbed; (d) incident radiation from the ground, absorbed; and (e) incident radiation from the atmosphere, absorbed. In general, (e) is probably negligible. None of the other four items can be neglected.

My calculations, as well as simple argument based on theory, show that *for steady conditions*, it would be a rare case indeed in which the use of aluminum paint did not result in higher temperatures. The only exception where the black paint should show a higher rise, is when a disconnected transformer is sitting in strong sunlight, surrounded with air at something like 30 deg. cent., and surrounded by a ground (such as rock, sand) whose surface has gone up to something like 80 deg. cent.

I believe that in all usual conditions the black surface should show the lesser rise.

There are two questions that should be raised about the Wetherill-Montsinger paper. First, if all factors except paint used were made exactly equal, and if the tests were conducted under steady conditions, *in still air*, would not the aluminum and white paints show the higher temperatures in top oil? Second, should not *color* of paint be suppressed in papers dealing with radiation? It is true that when we are concerned with the sun's radiation alone, color is important, simply because so much of the energy is in the visible part of the spectrum; but for ground radiation, and for most cases of low-temperature radiation, the color of the receiving surface is usually one of the least important characteristics of the surface.

If transformers had to do without convection dissipation, an aluminum or white paint (that is, a low-emissivity paint) would cause a higher ascent of temperature over the "black" surface temperature, than would occur with convection present.

Power Transients in A-C. Motors
A Watt-Oscillograph Study

BY L. E. A. KELSO[1] and G. F. TRACY[1]
Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—The purpose of this paper is to describe the application of the watt-oscillograph to the study of the performance of rotating a-c. machinery under transient conditions. Some typical transient cases are presented with a view to illustrating the possibilities of such an application. The analysis of a film taken with the watt-oscillograph yields not only power, but also current and power factor. It is thus possible, for the case of sinusoidal voltages and currents, to determine the locus of the current vector as it changes from one position to another.

The paper also describes the watt elements of the oscillograph developed for this study, with data as to the degree of accuracy that may be expected from them. An outline of the method of analyzing an oscillogram so as to obtain the performance curves and the current locus is also given.

I. The Watt-Element and Its Use

1. *Introduction.* The watt-oscillograph not only serves the primary purpose for which it has been developed, namely, that of recording the instantaneous values of power in an a-c. circuit; but, in the case of sinusoidal voltages and currents, its records also permit of the determination of the magnitude and the phase relation of the current with respect to the voltage. This determination may be made for transient as well

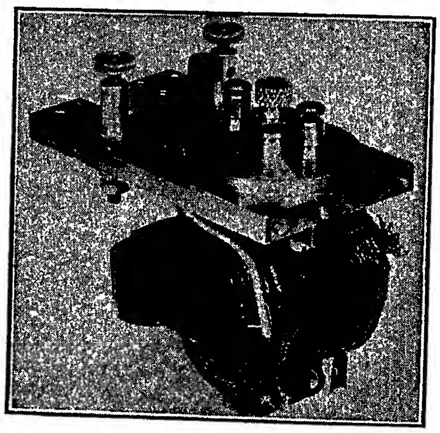

Fig. 1A—Illustration of Watt Element

as steady-state conditions, and therefore the locus of the current vector as it changes from one position to another may be determined. Such an analysis has proved to be particularly applicable to the study of transient conditions in three-phase a-c. motors, as, for example, the behavior of a synchronous motor following a change of mechanical load. The changes in the magnitudes and in the phase relations of the currents in such transients take place relatively slowly so that a reliable analysis may be made throughout the whole of the transient period. In cases where the duration of the transient is only a very few cycles it is difficult to obtain reliable analyses by means of the watt-oscillograph.

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2. *Description of the Watt-Element.* Illustrations of a single-phase watt-element as developed for these studies are shown in Figs. 1A and 1B. The magnetic circuit consists of twelve strips of 14-mil silicon steel, each strip being 1.43 cm. wide. The length of the iron path is 12 cm., and that of the air-gap 0.07 cm. In order to minimize leakage flux and iron loss, the two exciting coils of 37 turns each are placed close to the air-gap as shown in Figs. 1A and 1B. The rated field current is 3.54 amperes (peak value) and the corresponding exciting m. m. f. is 262 ampere-turns (peak value). At this excitation the flux density in the air gap is approximately 4700 maxwells per sq. cm., and in the iron it does not exceed 5000 maxwells per sq. cm. The volt-ampere load of the field winding at rated excitation is only 1.5 volt-amperes. An element, therefore, can be connected in the secondary circuit of a standard current transformer without imposing any appreciable additional burden on the transformer.

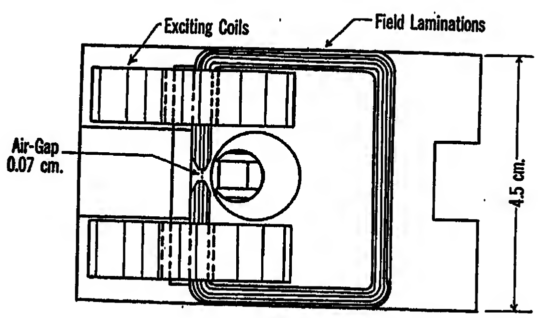

Fig. 1B—Plan View of Watt Element (from below)

Three elements are mounted in a holder which is easily interchangeable with the standard holder in a three-element Westinghouse portable oscillograph. In order to obtain sufficient deflection the vibrators used are the Westinghouse super-sensitive vibrators rather than the standard vibrators. These are oil damped. The full scale deflection of 4.5 cm. peak to peak is obtained with a field excitation of 3.54 amperes (peak value) and 0.0424 ampere (peak value) in the vibrator.

The accuracy of the instrument was tested by

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connecting each element in a simple a-c. circuit in which both the magnitude of the current and its phase with respect to the voltage could be varied at will. Two groups of films were taken, and the results obtained from these were checked against the readings of calibrated meters. One group consisted of a series of records at unity power factor and various values of field current; the other, at a given field current and various power factors. The current through the vibrator was held constant. The former test showed that the values of volt-amperes as calculated from the oscillograph records were within 1.4 per cent of the corresponding meter readings. The latter test showed that with phase angles from about 30 deg. to 90 deg. the maximum error was less than 4 deg. The accuracy with which the phase angle may be determined decreases, however, as the angle approaches zero; and in the neighborhood of zero the phase angle cannot be found within about 10 deg. This is not a disadvantage in the case of three-phase power measurement as will be pointed out later. It was apparent from these results that with suitable ranges of field and vibrator currents any errors caused

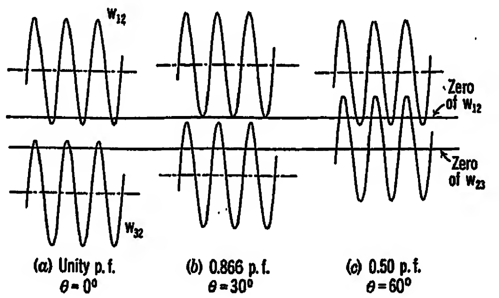

FIG. 2—TYPICAL THREE-PHASE POWER CURVES

by magnetic saturation and hysteresis in the iron circuit are no greater than those ordinarily incurred in measuring distances on an oscillogram. It may be said, then, that the flux densities in the air-gap are substantially proportional to the current in the main circuit, and that the deflection of the vibrator is substantially proportional to the instantaneous power.

3. Interpretation of the Oscillograms. It will be recalled that if the voltage and current in a single-phase circuit vary sinusoidally the instantaneous power curve is a double-frequency sinusoid the peak value of which is proportional to the volt-amperes and the axis of which is displaced from the zero line of the power curve by a distance proportional to the average power. Since the ratio of average power to volt-amperes is the power factor, the latter may be found by taking the ratio of the displacement of the axis of the power curve to the peak value of the double-frequency sinusoid. If an oscillogram of a power curve is taken during a transient condition so that power, power-factor, and current are varying, the value of these quantities may be found for all points on the film provided that the vibrator has been properly calibrated.

Either two or three single-phase elements may be used to measure power in three-phase circuits. When two elements are used they are connected in the same way that two single-phase wattmeters would be used to measure three-phase power, with the exception that it is preferable to reverse the potential connections of one element. The two elements trace out two power curves, each having the same characteristics as the single-phase curve. The total power is the sum of the powers indicated by each element, irrespective of load balance.

If the voltages and currents are sinusoidal and balanced, the expressions for the two power curves are:

$$w_{12} = E\,I\,[\cos(\theta - 30°) - \cos(2\,\omega\,t - 30° - \theta)]$$

$$w_{32} = E\,I\,[-\cos(\theta + 30°) - \cos(2\,\omega\,t - 30° - \theta)]$$

where E is the r. m. s. voltage between lines, I is the r. m. s. line current, and θ is the angle between phase current and phase voltage. The double-frequency components of the two curves are in phase with each other, and have the same amplitudes. The axis of the curve w_{12} is displaced *above* its zero line by a distance proportional to cos $(\theta - 30°)$ while the axis of the curve w_{32} is displaced *below* its zero line by a distance proportional to cos $(\theta + 30°)$. The phase angle, θ, at any point on an oscillogram may therefore be found from either power curve. The value found from one curve may be checked against that found from the other, as the two values should be the same for balanced conditions. The angle between the current in the field and the voltage across the potential terminals in one element differs by 60 deg. from the angle between the current and the voltage in the other element. Therefore, when that angle in one element is in the neighborhood of zero degrees so that it cannot be determined accurately as previously pointed out, the corresponding angle in the other element is in the neighborhood of 60 deg. at the same time, and may be determined accurately.

The disposition of the two power curves for three typical power factors in a balanced three-phase circuit is shown in Fig. 2. When the power factor is unity both curves are displaced from their zero lines by equal distances, the first up and the second down, as in Fig. 2A. When the phase angle is 30 deg., as in Fig. 2B, the displacement of one of the curves is a maximum, *i. e.*, the tips of the double-frequency sinusoid just touch the zero line. In Fig. 2C the axis of one of the power curves is not displaced at all. If the potential terminals of one of the elements had not been reversed the two curves would have been 180 deg. out of phase, and the tips of the curves would overlap, making it more difficult to distinguish them clearly.

II. TYPICAL CURRENT LOCI

The following section of the paper contains the results obtained from the analyses of the watt-oscillograph records taken of a few typical transient conditions in three-phase induction and synchronous motors. The performance curves and current locus corresponding to each case are shown. On each oscillogram are three

curves, two of power and one of line voltage. In analyzing an oscillogram the envelopes of the two curves were drawn and ordinates were erected at suitable equal intervals, usually at every cycle on the voltage wave. The peak values of the double-frequency com-

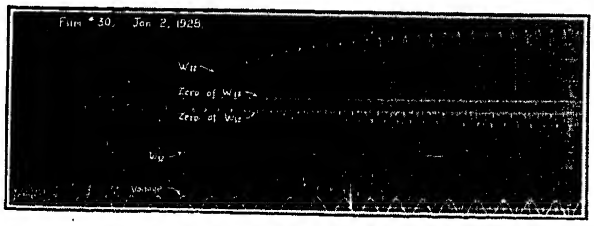

FIG. 3A—RATED LOAD THROWN ON INDUCTION MOTOR (FILM 30)

ponents of the power curves and their displacements from their respective zero lines were measured at each ordinate. A calibration film was taken to accompany each film of a transient condition, and the volt-ampere constant and voltage constant were obtained from it.

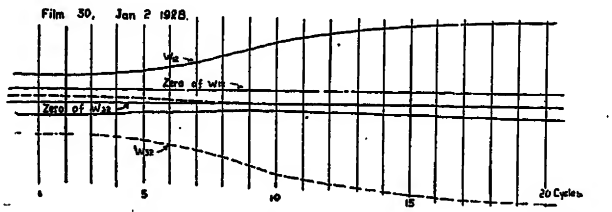

FIG. 3B—POWER CURVE ENVELOPES OF FILM 30

The calibration film was taken with a steady-state load and corresponding meter readings were obtained. In the following discussion each oscillogram is accompanied by a tracing of the envelopes of the power curves

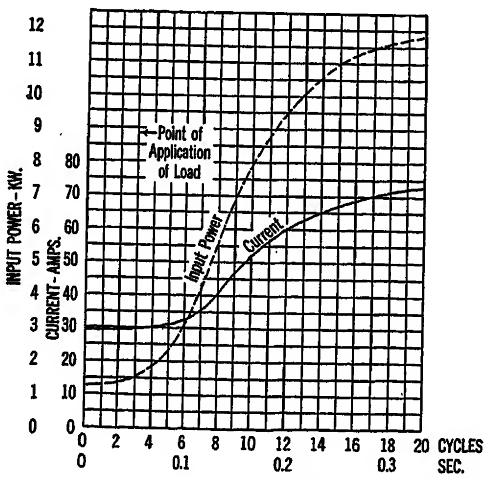

FIG. 3C—PERFORMANCE CURVES FROM FILM 30

15-hp. induction motor, 110–220-volt, 78.8-ampere, 60-cycle, 1200-rev. per min.

showing the ordinates at which the measurements were made. In each case the envelope of one curve has been shown by full lines and that of the other by dotted lines.

4. *Induction Motor Transients.* Power curves taken while rated load was being thrown on a 15-hp. induction motor are shown in Figs. 3A and 3B. The corresponding performance curves and current locus are shown in Figs. 3C and 3D. The load, which consisted of a generator direct-connected to the motor, was thrown on at about ordinate 2 and the current and power then increased steadily from their no-load values to approximately their full-load values at ordinate 20. The magnitude of the current and its phase angle with respect to the voltage were determined at each of the ordinates 1 to 20. Only the no-load and the full-load current vectors have been drawn, but the locus of the end of the current vector as it moves from one of these positions to the other has been shown. The numbered positions on this current locus correspond to the numbers of the ordinates on Fig. 3A. Since these ordinates were erected at equidistant intervals on the oscillogram

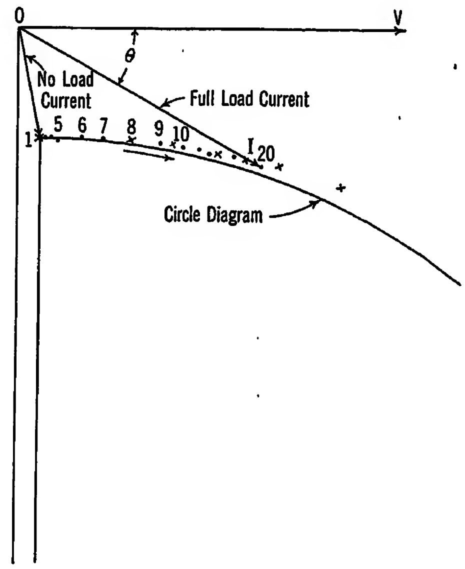

FIG. 3D—CURRENT LOCUS FROM FILM 30

Points marked (.) from Film 30
Points marked (x) from load test data

it means that the corresponding points on the current locus represent equal intervals of time. An indication, therefore, of the rate at which the phase position of the current vector changes, may be obtained from the distances between the points on the current locus. The phase position changes most rapidly, for example, in the vicinity of ordinate 8.

A check on the current locus as obtained from the oscillogram was made by laying out a similar locus from an ordinary load test in which the points were obtained from meter readings. It will be noticed that the two loci coincide. This is to be expected in the case of an induction motor in which the load is gradually applied, since there should be no tendency toward oscillations. The circle diagram of the motor, constructed in the usual way, is also shown.

Figs. 4A to 4D show the case of the breakdown of a

7.5-hp. induction motor. A heavy overload was thrown on the motor so that the speed dropped nearly to zero by the time the film exposure was completed. The circle diagram of this machine is also shown.

5. Synchronous Motor Transients. Figs. 5A and 5B show the power curves taken while rated load was being thrown on a 15-kv-a. synchronous motor. The load consisted of a d-c. generator as in the induction

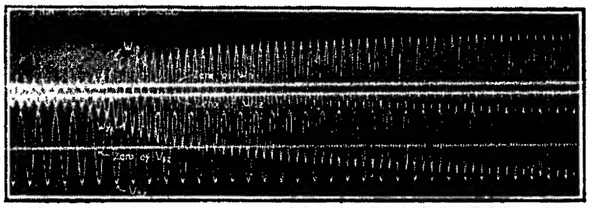

FIG. 4A—BREAKDOWN OF INDUCTION MOTOR (FILM 109)

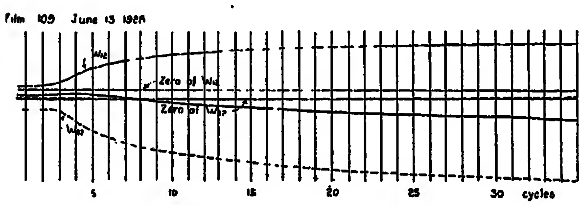

FIG. 4B—POWER CURVE ENVELOPES OF FILM 109

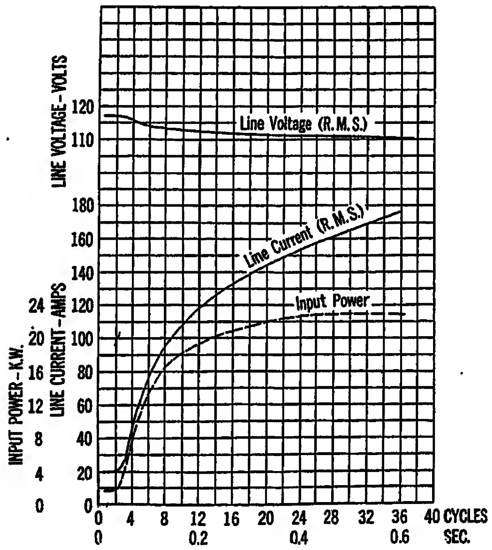

FIG. 4C—PERFORMANCE CURVES FROM FILM 109

7.5-hp. "Self-Start" motor, 1160-rev. per min., 110-volts, 39-amperes, 60-cycles

motor case. The excitation of the motor was adjusted so that the power factor was unity at full load. The power and current start to increase at about ordinate 6 and build up to values that are greater than the ultimate steady-state values. After two or three oscillations both settle down into their steady-state, full-load values. The actual point of throwing the load on was about ordinate 2 and not at ordinate 6. There is a dip in both the power and current curves which is caused, presumably, by a disturbance in the circuit which was used to excite the fields of both the motor and the d-c. generator, when the field circuit of the latter was closed.

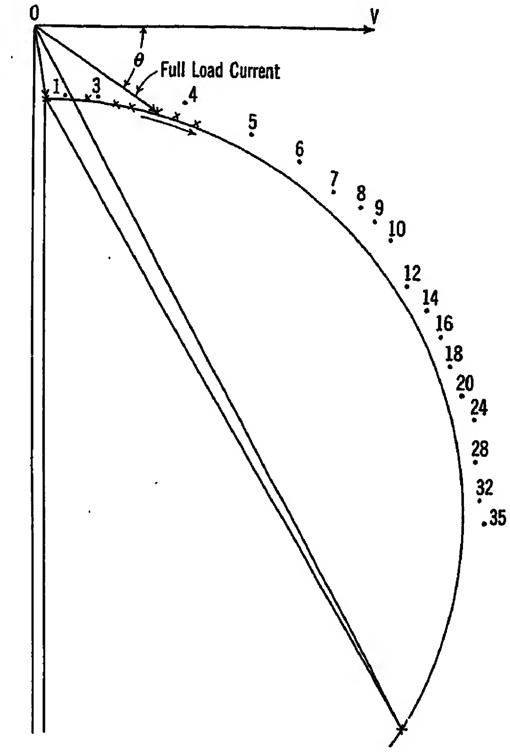

FIG. 4D—CURRENT LOCUS FROM FILM 109

Points marked (.) from Film 109
Points marked (x) from load test data

The current locus in Fig. 5D corresponds to Fig. 5A, and is a peculiar curve which roughly resembles an elongated spiral. Ordinate 1 is the position of the

FIG. 5A—RATED LOAD THROWN ON SYNCHRONOUS MOTOR (FILM 68)

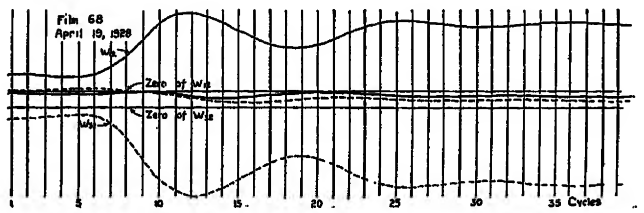

FIG. 5B—POWER CURVE ENVELOPES OF FILM 68

current vector I at no load. It is seen that the locus has a small hook in it which corresponds to the initial dip in the current and power curves. The vector then

travels out along a smooth curve through ordinates 7 to 12 as the load builds up. Its angular velocity is high in the vicinity of ordinates 8, 9, and 10 as indicated by the interval between these points. Maximum power is being drawn from the line at ordinate 12. It is apparent

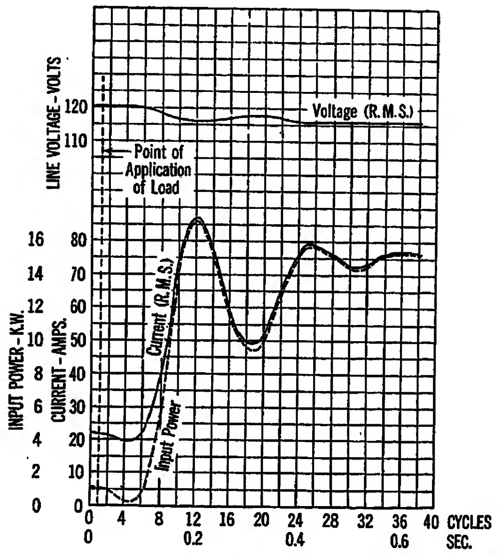

FIG. 5C—PERFORMANCE CURVES FROM FILM 68

15-kv-a., a-c. generator, 110–220-volt, 78.8 ampere, 60-cycle, 1200-rev. per min.

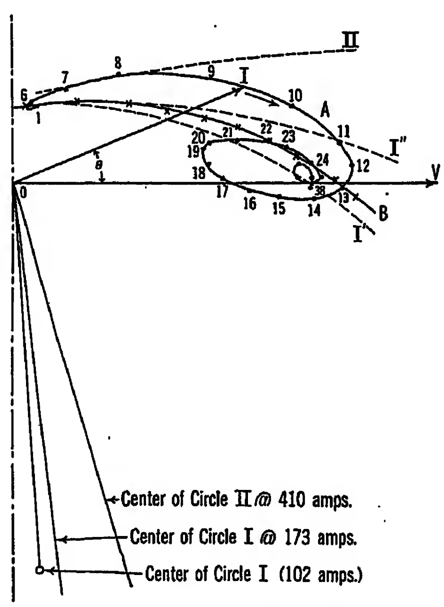

FIG. 5D—CURRENT LOCUS FROM FILM 68

Curve *A* from Film 68
Curve *B* from load test data
Circles *I'* and *I''* are synchronous impedance circles
Circle *II* is a leakage impedance circle

that the ultimate position of the current vector is in the vicinity of ordinate 38, *i. e.*, in phase with the voltage vector. On the same diagram has been shown the corresponding current locus as computed from load test data. These points fall on the familiar circular locus, and since the excitation was adjusted for unity power factor at full load the angle θ is nearly 90 deg. leading at no-load.

An explanation of the peculiar shape of the current locus in Fig. 5D may be given, by using the same methods and approximations as those of the Blondel circle diagram. When the motor is running at no-load its generated voltage vector is almost in phase opposition to the impressed voltage; while if the load is increased, the generated voltage vector lags farther behind its position at no-load. In the former case the resultant voltage acting across the impedance of the armature is very small, while in the latter case it is quite large (assuming that the magnitudes of the generated and impressed voltages are approximately the same). The current in each case is proportional in magnitude to the resultant voltage and lags behind it by an angle of nearly 90 deg. The vector diagram of Fig. 6A shows the position of the vectors for five different steady-state loads. This diagram is for the case where the excitation of the machine is such as to give unity power factor at full load. The locus of the end of the current vector is one of the constant-excitation circles of the Blondel diagram.

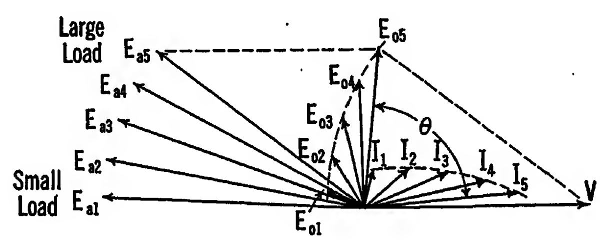

FIG. 6A—VECTOR DIAGRAM OF SYNCHRONOUS MOTOR

In Fig. 6A the vectors E_{a1} to E_{a5} represent the *excitation* voltage of the motor and not the *generated* voltage, for the magnitude of the latter is not constant; but, on account of armature reaction, varies as the load is changed. The relationship between any resultant-voltage vector and the corresponding current vector is therefore the *synchronous* impedance of the armature, and not the *leakage* impedance. It will be recalled that the use of the synchronous impedance accounts for armature reaction, because the magnetomotive force of the armature is assumed to be replaced by a fictitious reactance which is added to the leakage reactance of the armature, the combination of the two reactances being called the synchronous reactance. Thus in Fig. 6A, $I = E_0/z_s$ and $\theta = \tan^{-1} x_s/r_e$; where z_s is the synchronous impedance, x_s is the synchronous reactance, and r_e is the effective resistance. One of the constant-excitation current loci of the Blondel diagram is shown by circle *I* in Fig. 6B. This current locus corresponds to that shown in Fig. 6A. The center of circle *I* is at point *C* which is distant from *O* by an amount equal to V/z_s, and the angle between *O V* and *O C* is $\tan^{-1} x_s/r_e$. The vector *V* represents the impressed voltage.

Suppose that the armature reaction could be prevented in some way from changing the flux in the field poles. Such would be the case, for example, if either the field circuit or the damping grids had zero resistance so that the field flux were not allowed to change for an infinitely long time. This condition would mean that the additional fictitious reactance that replaces armature reaction is zero. The relation between the resultant voltage and the current is now E_0/z_a instead of E_0/z_s as it was before, where z_a is the transient or leakage impedance of the machine; and the currents, therefore, will be correspondingly larger and will not lag behind the corresponding resultant voltages by so large an angle because x_a is smaller than x_s. The current locus can now be shown to be another circle such as circle *I I* in Fig. 6B with center C' on a line $O\,C'$ which is displaced from the voltage vector by an angle $\tan^{-1} x_a/r_e$ and at a distance from O equal to V/z_a.

The two circles *I* and *I I* of Fig. 6B represent two extreme conditions. Circle *I I* is the locus of the

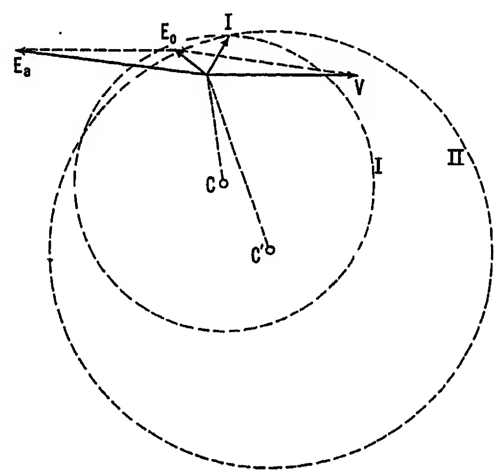

FIG. 6B—CURRENT LOCI OF SYNCHRONOUS MOTOR

current vector if the flux is prevented in some way from changing at all under the influence of armature reaction. Circle *I* is the locus if the flux readily follows the changes in resultant magnetomotive force. This latter locus is the one that would be traced out if the data from an ordinary load test are plotted; for in such a test the load is increased in steps and there is plenty of time for the flux to change to a new steady value between each step. This circle, then, might be thought of as the current locus when the load is very slowly increased. When full load is applied all in one step, however, the current at first will tend to follow circle *I I* because the flux cannot change readily on account of the damping action of the field circuit and of the damping grids. Then, as the flux gradually yields to the effects of the armature magnetomotive force the current vector will gradually move across to circle *I*.

Referring again to Fig. 5D, circles similar to those which have just been discussed are shown on this figure. Circles I' and I'' on Fig. 5D both correspond to circle *I* on Fig. 6B; *i. e.*, they are both synchronous impedance circles, but the value of the synchronous impedance was measured by two different methods. The value of z_s for circle I' was obtained from short-circuit test data while that for circle I'' from the zero power-factor test data. It is seen that the actual current locus as found from the load test falls between these two circles. Circle *I I* of Fig. 5D corresponds to circle *I I* in Fig. 6B; *i. e.*, its center was found by using the leakage impedance. The value of the leakage impedance was determined by the Potier method from the open-circuit and zero power-factor characteristics.

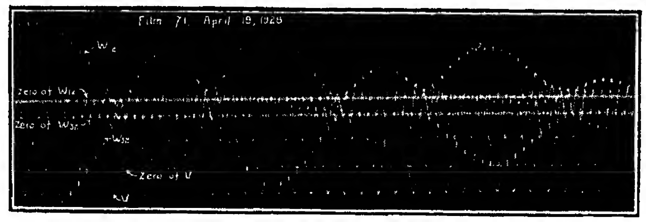

FIG. 7A—RATED LOAD THROWN OFF SYNCHRONOUS MOTOR (FILM 71)

It can be seen that the current locus for a rapidly increasing load actually tends to follow this circle at first, and then moves across to the other current locus as predicted in connection with Fig. 6B. The field structure reaches the farthest point in its swing about ordinate 12, at which point the voltage vector comes to rest; and starts to swing back again because it has overshot its ultimate position. During this time the armature reaction has had time to change the field flux and bring the current vector completely over to its steady-state locus. However, as the field structure swings back again the flux is again slow in changing, this time in the

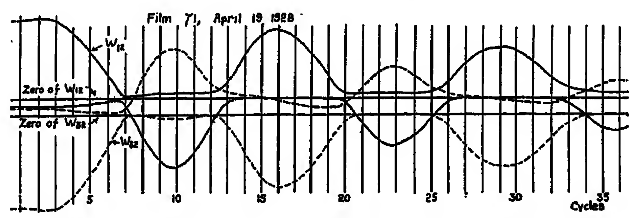

FIG. 7B—POWER CURVE ENVELOPES OF FILM 71

opposite direction; and so the current vector swings down below its steady-state locus. After two or three oscillations the hunting of the field structure dies out and the flux and current settle into their steady-state full-load positions.

Figs. 7A to 7D are for the case of rated load being thrown off a 15 kv-a. synchronous motor. The hunting is very apparent in this case as it persists for a long time. The field structure swings backwards and forwards around its no-load position going alternately into the region of generator action and the region of motor action. The power bands cross and re-cross each other in Figs. 7A and 7B, and the power curve in Fig. 7C goes

alternately positive and negative. The current locus shows characteristics similar to the one for the case of load thrown on the motor. It is obvious that the current vector will ultimately settle down into its no-load position as shown by position 1 in Fig. 5D.

Figs. 8A to 8E are for the case of a 15-kv-a. syn-

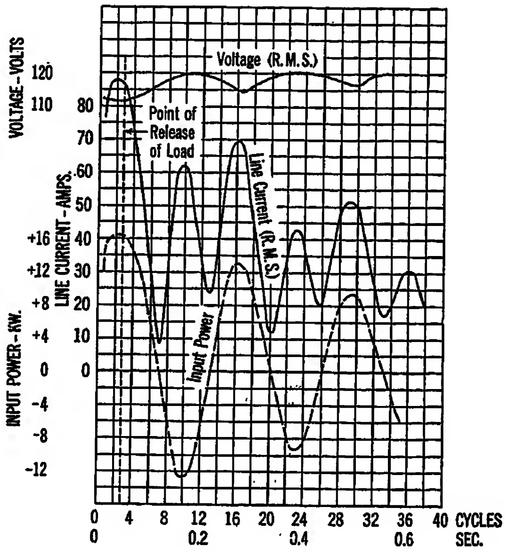

FIG. 7C—PERFORMANCE CURVES FROM FILM 71

15-kv-a., a-c. generator, 110–220-volt, 78.8–39.4-ampere, 60-cycle, 1200-rev. per min.

chronous motor pulling out of step. The load was allowed to build up to a value which was beyond the maximum torque of the motor. In this case a contactor, mounted on the shaft of the motor, was con-

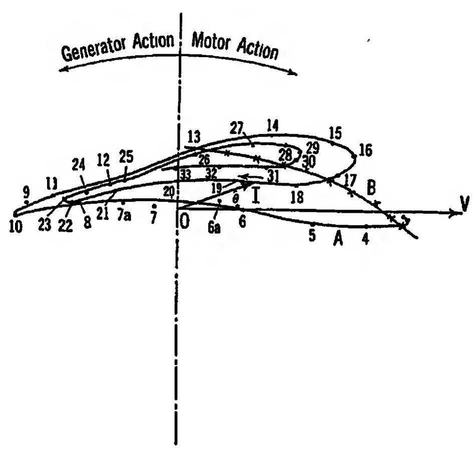

FIG. 7D—CURRENT LOCUS FROM FILM 71

Curve *A* from Film 71
Curve *B* from load test data

nected so as to momentarily short circuit the voltage element at one point in each revolution of the motor shaft. As the machine was a six-pole machine this momentary short circuit would occur once every third cycle on the voltage wave if the machine were running in synchronism. The discontinuities in the voltage wave can be seen in Fig. 8A. After the application of load the intervals become greater than three cycles, indicating that the machine is slowing down. These marks afford a means of checking roughly the phase position of the field structure and of the excitation

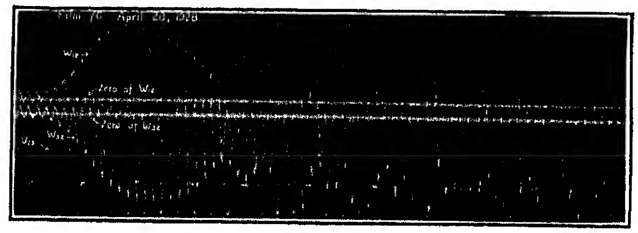

FIG. 8A—SYNCHRONOUS MOTOR PULLING OUT OF STEP (FILM 76)

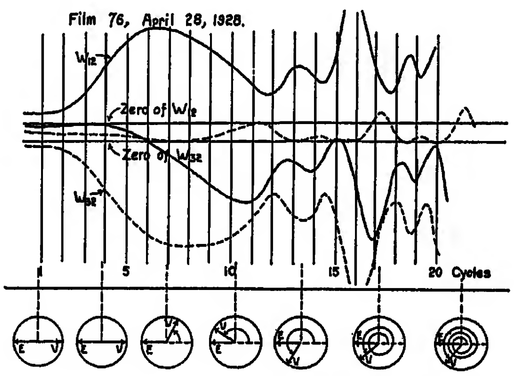

FIG. 8B—POWER CURVE ENVELOPES OF FILM 76

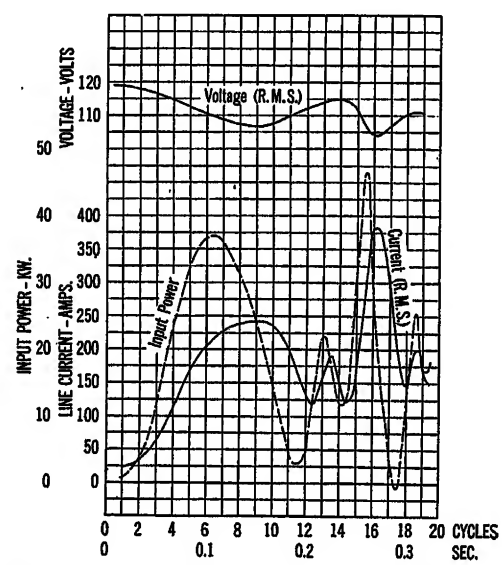

FIG. 8C—PERFORMANCE CURVES FROM FILM 76

15-kv-a., a-c. generator, 110–220-volt, 78.8–39.4-ampere, 60-cycle, 1200-rev. per min.

voltage, E_a, at the points at which they occur. If normal load had been applied these marks would have shifted to a new steady position on the voltage wave, the distance between the old and new positions being the angle of coupling for that loa

A group of vector diagrams is shown beneath the curve in Fig. 8B which indicate the phase position of the field structure (as shown by the excitation voltage vector E) at the points of discontinuity on the voltage wave. In these diagrams the vector E has been made the reference vector because the points of short-circuit were made at even revolutions of the motor shaft; *i. e.*, at integral numbers of cycles of E. Thus at point 7 the motor shaft has made exactly two revolutions after passing point 1; *i. e.*, E has gone through exactly 6

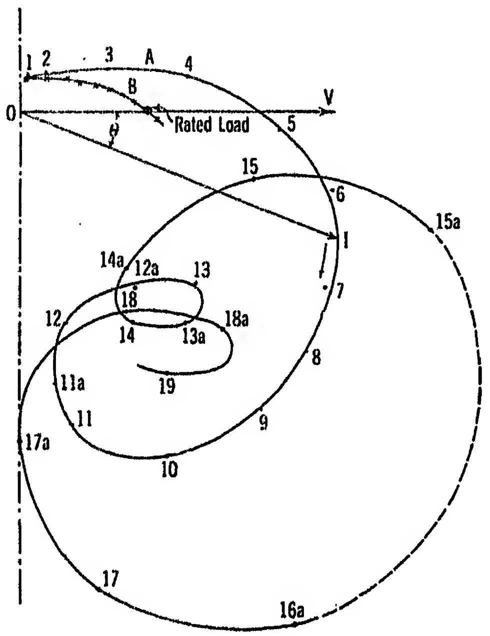

FIG. 8D—CURRENT LOCUS FROM FILM 76

Curve A from Film 76
Curve B from load test data

cycles, but the applied voltage has gone through 6 cycles and about 60 deg. in addition.

By referring to the power curve in Fig. 8C it is seen that the power reaches its first maximum about point 7. The phase relation between $-E$ and V is about 60 deg. in this position. The power does not reach its first minimum value until about point 12 at which the angle between $-E$ and V is about 180 deg. Then there is a small increase in power to point 13 after which it again passes through a minimum at point 14. The vector diagrams show the angle between $-E$ and V to be roughly 360 deg. at point 14, indicating that the rotor has dropped back a whole pair of poles and the power cycle is about to repeat itself. The second power cycle is similar to the first, the difference being that the power rises to a higher maximum value and the time of the power cycle is much less than that of the first cycle because the rotor is now slipping back at a greater rate. The most noticeable feature of this current locus is its departure from the circular locus of the Blondel circle diagram according to which the current should traverse a true circle (see circle I, Fig. 6B) for this case.

Fig. 8E was taken under the same conditions as Fig. 8A, except that the third element was used to record field current. The variations in field current show in a striking way how the field circuit is attempting to prevent the flux from changing. When the load first increases the field current also increases in an effort to counteract the increasing demagnetizing effect of the

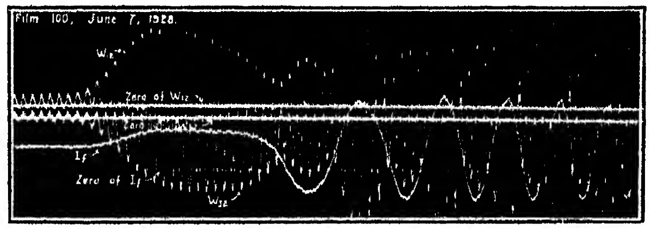

FIG. 8E—FIELD CURRENT UNDER SAME CONDITIONS AS FILM 76

armature current. This sudden increase in field current is repeated every time the field structure pulls away from a pair of armature poles of the correct polarity to produce motoring torque.

III. CONCLUSION

The foregoing illustrations demonstrate a field of usefulness for the watt-oscillograph which is much broader than merely that of recording instantaneous power. The current loci show graphically certain characteristics of a-c. motors which, it is believed, have not been obtained experimentally by other methods. Such loci should prove useful in a theoretical study of the operation of these machines under transient conditions. It is believed that this application of the instrument will be extended to include many other types of transients.

The authors gratefully acknowledge the many suggestions given them by Professor Edward Bennett and Professor J. R. Price of the Department of Electrical Engineering, University of Wisconsin.

The General Circle Diagram of Electrical Machinery

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Synopsis.—The well known circle diagram of a transmission network is applied to electrical machinery, giving circle diagrams of alternators, synchronous motors, synchronous condensers, and transformers. These diagrams give a graphical representation of the machine performance under all possible conditions. Such quantities as power loss, power input, power output, field current, etc., for any operating condition can be obtained by inspection. These diagrams have the same field of usefulness as the circle diagram of the induction motor.

The transmission network circle diagram can be applied to the induction motor, yielding in the approximate representation the Heyland diagram, which is merely a special case of the more general diagram. The transmission network method of attack gives a straight-forward solution of many induction motor problems that would otherwise be difficult to handle, such as a motor equipped with a phase advancer.

Methods of obtaining network constants by measurements rather than computations are described.

INTRODUCTION

Any electrical network connecting two pairs of terminals can have its electrical characteristic expressed in terms of four constants A, B, C, and D through the equations

$$E_s = A\,E_r + B\,I_r$$
$$I_s = C\,E_r + D\,I_r \qquad (1)$$

or the equivalent equations

$$E_r = D\,E_s - B\,I_s$$
$$I_r = A\,I_s - C\,E_s \qquad (2)$$

The subscripts s and r denote sending and receiving and quantities, respectively. The coefficients A, B, C, and D, which are known as *network constants*, take into account the composition of the transmitting network and the frequency. They can be readily obtained for any particular case by methods and formulas that have been worked out by Evans and Sels,[1] or by the measurements described in Appendix I. Only three of the four constants are independent, since the relationship $A\,D = I + B\,C$ must always exist between them. For a symmetrical network $A = D$.

When either the sending end or the receiving end voltage is constant, the electrical properties of the network can be represented graphically by a circle diagram consisting of families of circular loci drawn on a power—reactive power coordinate system. This circle diagram is a graphical representation of Equations (1) and (2), and when once drawn, an inspection of the one diagram will give such quantities as power, current, admittance, and power factor at both sending and receiving ends of the network, also efficiency of transmission, power lost in transmission, and so on almost without limit.

A coordinate system of sending end power and reactive power is used when the sending end voltage is constant, while received power—reactive power coordinates go with a constant receiver voltage. In either case, the diagram can be readily constructed by laying out the proper system of power coordinates, computing the centers and radii of the desired circles from the network constants according to formulas that have been derived,[2] and doing the rest with a compass. After this has been done the results can be gone over for errors by applying a series of simple graphical checks.

The circle diagram as described was developed for the purpose of representing the properties of power lines and transmission networks. In a highly specialized form this general circle diagram becomes the well known induction motor circle diagram. In both applications this graphical method has been of inestimable value because it shows on one drawing all possible conditions. After the circles have once been laid out no further computations are necessary, and a complete visualization of the network performance is easily obtained.

The circle diagram method of graphical representation can be used to show the performance of alternators, synchronous motors, transformers, and synchronous condensers with the same advantages that are already well known in the cases of the transmission line and the induction motor. The transmission network circle diagram is applied to such electrical equipment by substituting for the actual machine an equivalent electrical network for which a circle diagram is then drawn. The details of the transformation from machine to electrical network, and the special problems involved are taken up in the following sections.

CIRCLE DIAGRAM OF THE TRANSFORMER

The action that takes place in a transformer is

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1. Evans and Sels, *Power Limitations of Transmission Systems*, A. I. E. E. TRANS., Vol. 43, 1926, p. 26. Also a series of articles by Evans and Sels in *Electric Journal*, 1921.

2. F. E. Terman, *The Circle Diagram of a Transmission Network*, A. I. E. E. TRANS., Vol. 45, 1926, p. 1081.

accurately given by the well known network shown in Fig. 1, which has the network constants

$$A = D \doteq 1 + Z\,Y/2$$
$$B = Z\,(1 + Z\,Y/4)$$
$$C = Y \qquad (3)$$

Ratios of voltage transformation other than the unity value to which Equations (3) apply can be taken into account in the network constants. Calling the ratio of primary to secondary voltage N (N more than one

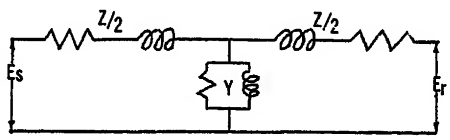

FIG. 1—EQUIVALENT CIRCUIT OF TRANSFORMER

Z-Series resistance and reactance representing primary and secondary copper losses and leakage reactance
Y-Shunt admittance representing core loss and magnetizing current

for a step-up ratio and N less than one for a step-down transformer), then when the transformer leakage reactance Z and admittance Y are referred to the secondary side, the network constants have the values

$$A = N\,(1 + Z\,Y/2)$$
$$B = N\,Z\,(1 + Z\,Y/4)$$
$$C = Y/N$$
$$D = (1 + Z\,Y/2)/N \qquad (4a)$$

When Z and Y are referred to the primary side the network constants become

$$A = N\,(1 + Z\,Y/2)$$
$$B = Z\,(1 + Z\,Y/4)/N$$
$$C = Y\,N$$
$$D = (1 + Z\,Y/2)/N \qquad (4b)$$

Equations (3) and (4) consider the leakage reactance equally distributed between primary and secondary, which is the usual assumption. Network constants for other divisions are readily obtained by using methods outlined by Evans and Sels.

The circle diagram of the transformer is a transmission line type of circle diagram drawn for the network constants given in Equations (4). When applied to an actual example the result is as shown in Fig. 2, which has been drawn for a 1000 kv-a. transformer operating with constant primary voltage. To avoid confusion, only power loss, power factor, and voltage circles are shown, although of course many other types of loci can be drawn when desired.

The transformer circle diagram gives a complete and *exact* graphical representation of the properties of the network shown in Fig. 1, and therefore shows the transformer performance to the same degree of precision as does the usual equivalent circuit. In constructing a circle diagram it is necessary that either the sending end (primary) voltage or the receiving end (secondary) voltage be kept constant. This restriction ordinarily involves no limitation to the usefulness of the diagram because transformers are normally supposed to operate with substantially constant voltage at one terminal.

The transformer is a very efficient piece of equipment, with small voltage drops and low losses. As a consequence some of the circles have large radii and appear to be almost straight lines on the diagram. This is the case with the secondary voltage and load power factor loci in Fig. 2, and is ordinarily to be expected. Circles too large for a beam compass can be readily drawn with the aid of a piano wire.

In drawing circles giving power dissipated in the transformer, great care must be taken in computing the circle radii, and it is necessary that the network constants A and D be known to a number of significant figures sufficient to incorporate to a fair accuracy the effect of the $Z\,Y$ term which they contain. Logarithm tables of at least five places are usually advisable in computations leading to the loss circles. Instead of computing the loss circles in the usual manner, it is more satisfactory under ordinary circumstances to obtain them by the much simpler method described in Appendix II.

It is of course possible to use equivalent transformer circuits other than that shown in Fig. 1. For example, the impedance Z can be considered as lumped in one piece, and placed either on the sending or receiving side

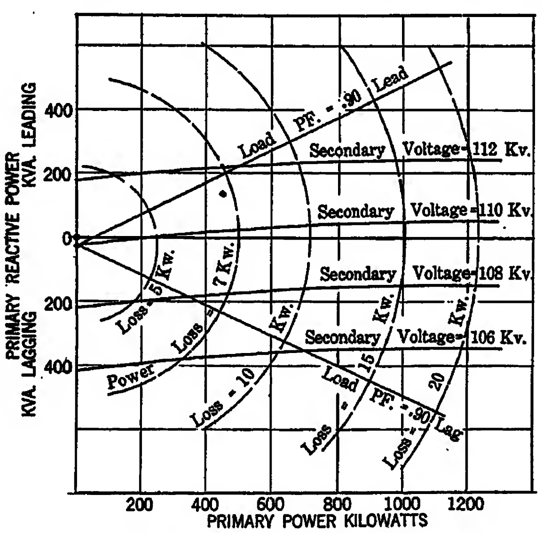

FIG. 2—CIRCLE DIAGRAM OF 1000-KV-A. TRANSFORMER WITH PRIMARY VOLTAGE KEPT CONSTANT WITH 110 KV.

of the admittance Y. Such an equivalent circuit has slightly simpler expressions for network constants than does Fig. 1, and involves only a slight approximation. In making approximations it is very necessary that the network constants be *exactly* the constants of the network in question. Simplifying the formulas for network constants by dropping apparently insignificant terms will sometimes yield amazing results. Thus dropping the $Z\,Y$ terms of A, B, and D in Equations (3) introduces an error in these constants of only about one per cent, but this omission is equivalent to neglecting *all* of the iron loss, and affects practically nothing else.

Circle Diagram of the Synchronous Motor

The performance of a synchronous motor can be shown by a circle diagram based on the equivalent circuit of Fig. 3, which represents one phase of the machine. In this figure E_r is the actual induced phase voltage, as determined by air-gap flux, E_s is the sending or terminal phase voltage, which is constant in the case of a motor, X_a and R_a are the armature leakage reactance and effective a-c. resistance (including armature copper and stray load losses), respectively, per phase,

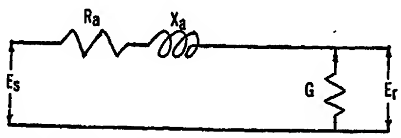

Fig. 3—Equivalent Circuit of Synchronous Motor and Synchronous Condenser

R_a – Series resistance representing armature copper and load losses
X_a – Series reactance representing armature reactance
G – Shunt conductance representing iron losses
E_s – Terminal voltage
E_r – Induced voltage

while the iron losses are accounted for by the conductance G. The motor is thus reduced to a transmission network through which power is transmitted with a sending end voltage of E_s and a receiving voltage of E_r. The power which in the equivalent circuit of Fig. 3 is delivered to the receiving voltage is the mechanical power produced by the motor and so is the shaft output plus the windage and friction. The motor losses exclusive of field loss are the losses in the equivalent circuit plus the windage and friction.

The network constants corresponding to Fig. 3 are

$$\begin{aligned} A &= 1 + G\,(R_a + X_a) \\ B &= R_a + X_a \\ C &= G \\ D &= 1 \end{aligned} \qquad (5)$$

In a given machine the usual stray power test will give R_a, G, windage, and friction. The iron losses can be represented by a conductance placed as shown in Fig. 3 because these losses are very nearly proportional to the square of induced voltage (and hence of air-gap flux). Since Fig. 3 applies to only one phase of the machine, in a polyphase motor the total iron losses are divided equally among the phases. An iron loss of P_i watts at an induced voltage of E_r accordingly leads to a conductance $G = (P_i/N)/E_r'^2$ in a machine with N phases. The leakage reactance X_a can be computed, or can be obtained approximately by measurement. The fidelity of the circle diagram is fortunately not appreciably affected by reasonable uncertainties in the value of X_a.

The circle diagram of the synchronous motor is based on the network constants of Equations (5), and is constructed in the usual way using a constant terminal voltage and a system of input power—reactive power coordinates. There is, however, considerable flexibility possible in the labeling of the diagram. Thus, although the equivalent circuit and hence the diagram obtained from it apply only to a single phase, it is possible to label this single-phase diagram with the corresponding three-phase quantities. The practical way of doing this is to compute the circle centers and radii on the single-phase basis, then lay out a coordinate system calibrated directly in three-phase power quantities and draw the circles using radii and center coordinates three times the calculated single-phase values. The circles themselves can also be marked with the corresponding three-phase values. Thus a circle representing a single-phase loss of 10 kw. can be marked 30 kw. on the three-phase diagram, and will then represent total three-phase loss.

The circle diagram as derived from Fig. 3 does not include windage and friction losses, but can be made to do so by a simple expedient. Since these losses represent mechanical power developed in the machine, but not available at the shaft, they can be taken into account by suitably labeling the diagram. That is, a loss circle would be drawn to represent a certain network loss but would be labeled with this loss plus the windage and friction loss, and an output power (receiver power) circle drawn representing a certain mechanical power output would be labeled with this power minus windage and friction, to give actual net shaft power.

The circle diagram of a 100-hp. synchronous motor is shown in Figs. 4 and 5, in which the labeling is in terms of three-phase quantities, and concludes windage and

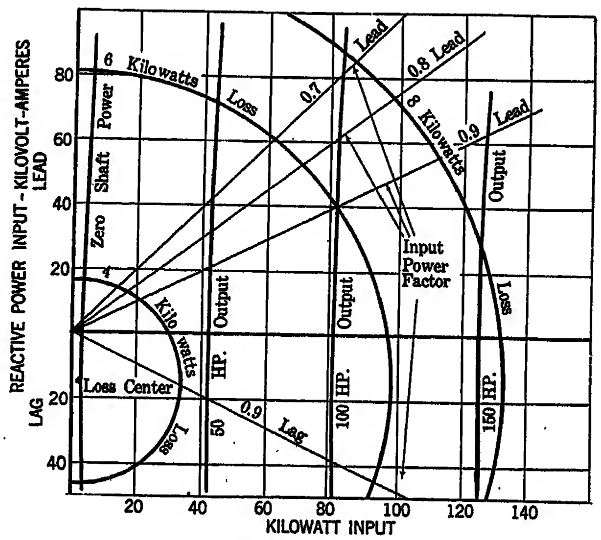

Fig. 4—Circle Diagram of 100-Hp. Synchronous Motor

friction. The motor diagram has been divided into two parts to avoid confusion, but by the use of colored inks all necessary loci could satisfactorily go on one figure. It is of course understood that Figs. 4 and 5 do not show all the circular loci that could be drawn. Loci giving input current, induced voltage, angle between terminal and induced voltage, etc., could have been included.

The usefulness of the synchronous motor circle diagram is greatly increased by superimposing constant field current lines upon the power—reactive power

coordinate system, as has been done in Fig. 5. The location of these lines can be obtained by either measuring or computing the combinations of reactive and real power that with the field current in question will give the terminal voltage for which the diagram is drawn. The field current loci are approximately circular arcs, and would be exactly circles if the armature reaction could be truly replaced by an armature reactance of constant value.

The circle diagram as described does not take into account field copper loss. It is possible, however, to mark each field current line with the corresponding

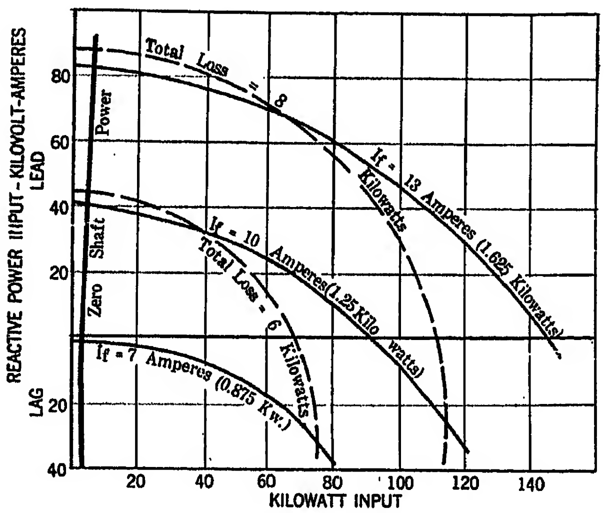

Fig. 5—Circle Diagram of 100-Hp. synchronous Motor (Fig. 4 continued)

field loss, and in this way to obtain from the circle diagram the total power loss of the alternator for a given load power and power factor. The procedure is to locate the point on the coordinate system corresponding to the desired load conditions. The field current line passing through this point shows the field power and the loss circle at the point gives the other losses (*i. e.*, windage, friction, armature copper, load, and iron) so that the total loss is the sum of these components. It is also possible to draw total loss loci, several of which are shown in Fig. 5. These lines are computed point by point from the loss circles and field current lines, and are almost but not exactly circular.

The accuracy of the motor circle diagram is approximately that of the usual stray power test method. The fundamental assumptions are: (1) iron losses are considered proportional to the square of the induced voltage and independent of armature current; (2) load losses are assumed proportional to the square of the armature current; and (3) the armature is assumed to have a constant leakage reactance. None of these assumptions introduces appreciable error.

In constructing the motor circle diagram some difficulty will be experienced in determining the radii of loss circles unless at least five place tables are used in computing radii and network constants. In most cases the approximate and simple method of drawing loss circles, given in Appendix II, is recommended as being the most satisfactory.

Circle Diagram of the Synchronous Condenser

Since the synchronous condenser is a synchronous motor operated without a shaft load, the circle in Figs. 4 and 5 for zero output represents synchronous condenser action. The entire discussion on the motor applies here without change, and so need not be repeated.

Circle Diagram of the Alternator

Since an alternator is merely a synchronous motor operated backwards, that is with power supplied to the shaft rather than taken from it, a circle diagram similar to that of the motor can be drawn for the alternator.

The equivalent circuit of the alternator is given in Fig. 6, and the corresponding network constants are

$$
\begin{aligned}
A &= 1 \\
B &= R_a + X_a \\
C &= G \\
D &= 1 + G\,(R_a + X_a) \qquad (6)
\end{aligned}
$$

The notation is the same as explained in connection with Equations (5).

The alternator circle diagram is drawn from these network constants in a manner similar to that followed with the synchronous motor. As in the case of the motor the final diagram can be labeled to represent three-phase quantities although the actual computations are on the basis of one-phase. Windage and friction losses, although not taken care of in the equivalent circuit, can be included by proper labeling. Thus the shaft driving power equals the windage and friction loss plus the three-phase sending end power of the equivalent circuit, and the total machine power loss is

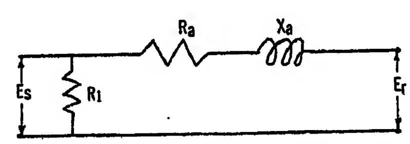

Fig. 6—Equivalent Circuit of Alternator

R_a - Series resistance representing armature copper and load losses
X_a - Series reactance representing armature reactance
G - Shunt conductance representing iron losses
E_s - Induced voltage
E_r - Terminal voltage

the windage and friction plus the three-phase loss indicated on the loss circle.

As in the case of the motor, lines of constant field current can be drawn on the coordinate system. These lines must be computed point by point, and are approximately but not exactly circular arcs. They can be marked with the field copper loss they represent, and in this way the diagram readily gives total loss exactly as in the case of the motor.

The circle diagram of a 25,000-kv-a. alternator is shown in Fig. 7. This diagram is drawn for a constant terminal voltage and so utilizes a coordinate system of

load (or receiver) power and reactive power. The labeling gives three-phase quantities and takes into account windage and friction losses. Thus, as the windage and friction is 122 kw., a loss circle computed for a single-phase loss of 76 kw. is marked as $3 \times 76 + 122 = 350$ kw. Only power loss and induced voltage circles are shown on Fig. 7, although many other types of circles could be added if desired.

The entire discussion given in connection with the motor circle diagram applies to the alternator diagram

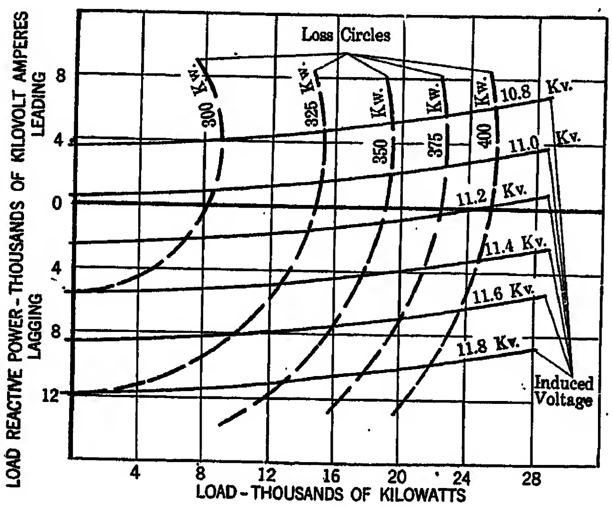

FIG. 7—CIRCLE DIAGRAM OF 25,000-KV-A. ALTERNATOR

with only minor and obvious modifications. In particular, the method given in Appendix II will generally be of considerable assistance in drawing loss circles.

CIRCLE DIAGRAM OF THE INDUCTOR MOTOR

The classical induction motor circle diagram is merely a special application of the more general circle

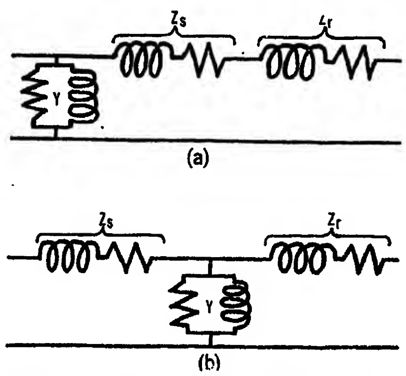

FIG. 8—EQUIVALENT INDUCTION MOTOR NETWORKS

Z_s = Stator impedance
Z_r = Rotor impedance reduced to stator side
Y = Shunt admittance representing iron losses, windage, and friction

diagram of a transmission network. This follows from the fact that the equivalent circuit of the induction motor is that of a transformer operating with a resistance load. Starting with the network constants of the equivalent induction motor circuit, a circle drawn for a unity power factor load is the operating circle of the usual motor diagram.

The equivalent circuit of the induction motor as used by different investigators varies somewhat, according to the assumptions made. The basis of the Heyland diagram is the equivalent circuit of Fig. 8A, which is only approximately correct. The more correct equivalent circuit of Fig. 8B also leads to a circle diagram, but one more difficult to draw.

The network constants corresponding to Fig. 8A are

$$\begin{aligned} A &= 1 \\ B &= Z \\ C &= Y \\ D &= 1 + Z\,Y \end{aligned} \qquad (7a)$$

while those applying to Fig. 8B are

$$\begin{aligned} A &= 1 + Z_s\,Y \\ B &= Z + Z_r\,(1 + Z_s\,Y) \\ C &= Y \\ D &= 1 + Z_r\,Y \end{aligned} \qquad (7b)$$

A transmission line type of circle diagram may be drawn for either of these equivalent circuits, or for any modified arrangement, using a constant terminal voltage, and input power—reactive power coordinates. In any case, the circle representing a unity power factor load is the operating circle of the motor, and the inter-

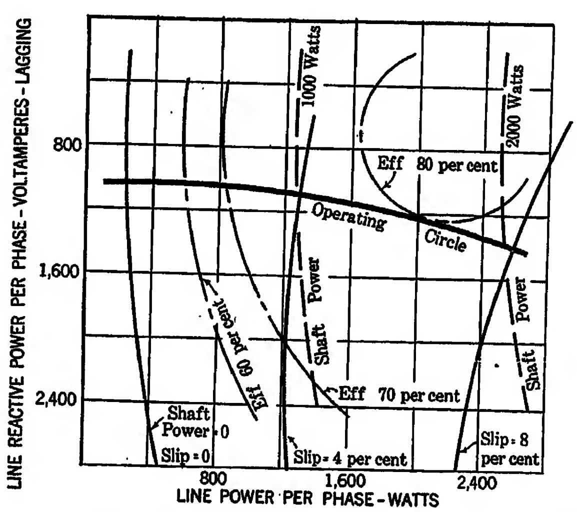

FIG. 9—CIRCLE DIAGRAM OF A SMALL INDUCTION MOTOR

sections of this circle with efficiency, power loss, power output, etc., circles give the motor performance. Also, since each load resistance in the equivalent circuit corresponds to a certain value of slip, load resistance (or conductance) circles can be labeled to give slip.

When the network of Fig. 8A and the network constants of Equations (7c) are used, the resulting diagram is exactly the well known Heyland diagram, which is accordingly only a special case of the general transmission network diagram, and the geometrical constructions commonly used to get slip, efficiency, etc., on the Heyland diagram are merely graphical means of

determining where different power loss, slip, and other circles intersect the unity power factor load arc.

A typical example of an induction motor circle diagram drawn by the transmission network method is shown in Fig. 9, which is based on the equivalent circuit of Fig. 8B, and is similar to the Heyland diagram, but slightly more accurate. By rotating Fig. 9 a quarter turn it will be readily recognized as an induction motor diagram.

Although any induction motor diagram can be drawn by following the transmission network mode of attack that has been outlined, such a procedure is not advisable where the usual Heyland diagram based on blocked rotor and no load tests will do. For this usual case, the classical procedure is so satisfactory and so well standardized that there is no incentive to replace it by something different, even if equally good.

The transmission network method of approach does, however, have a considerable field of usefulness in induction motor problems. For example, it gives a straightforward way of obtaining the operating circle when equivalent motor circuits other than that of Fig. 8A are used. Again, the usual construction for obtaining slip on the Heyland diagram is not accurate when the effective rotor resistance depends upon the slip frequency. This variation can be correctly taken into account in the network constant method of attack. The procedure is to assume a slip, and then draw a load conductance circle for a load resistance computed from the rotor resistance at the slip in question. The intersection with the operating circle gives the operating point for the slip in question.

An important use of the transmission network method of viewing the induction motor is in the analysis of problems where electromotive forces are introduced into the rotor circuit by commutator machines. The performance of induction motors equipped in this way can ordinarily be represented by some sort of a circle diagram, the exact nature of which depends upon the characteristics of the electromotive force generated by the commutator motor.[3]

An example that illustrates the power of the network constant method of attack is the case of induction motor in which a series commutator motor driven at constant speed is inserted in the rotor circuit. Such a machine, commonly called a phase advancer, is at its terminals equivalent to an impedance that is fixed both in magnitude and phase angle by the machine construction, and is independent of frequency. To incorporate in the circle diagram the effect of a phase advancer equivalent to a vector impedance Z one computes the network constants of the motor circuit assuming the rotor resistance is zero. Using these constants a circle is drawn corresponding to a load power factor represented by the phase angle of the impedance $R_r + Z$, where R_r is the rotor resistance. This circle is the operating circle of the motor when equipped with a phase advancer of the type mentioned. Slip, shaft power of the induction and commutator motors, etc., can be represented on the diagram by methods that are readily devised. An adequate discussion of this and similar cases would require a separate paper, however, and it is merely intended at this time to point out the possibilities of the transmission network method of attacking induction motor problems, particularly those out of the ordinary.

Induction generator action is represented by the negative power portion of the motor diagram so that the discussion that has been entered into applies to the induction generator with obvious modifications.

Representation of Machine Characteristics on a Power Coordinate System

In representing the relation between two variables it is customary to use a coordinate system in which one of these variables is plotted as a function of the other. Thus in a synchronous motor, one might plot efficiency as a function of shaft load, there being one such curve for each value of field current. Where a very comprehensive picture of machine performance is desired, however, it is preferable to use a power—reactive power coordinate system and to superimpose the desired loci upon this as has been done to a limited extent in Figs. 2, 4, 5, and 7. Lines representing such loci may be either circular or non-circular, depending upon the circumstances, but no matter how much saturation, etc., is present it is always possible to show correctly the complete performance of the apparatus on a single diagram.

The use of a power coordinate system to show characteristics has the advantage of permitting a ready visualization of the entire behavior under all conditions. From such a diagram it is possible to determine quantitatively the operating characteristics of a piece of equipment for a given set of conditions by inspection. Thus in the case of a synchronous motor which is to carry a certain load at a certain power factor, the point on the coordinate system that corresponds to this condition can be readily found from the power factor and load power loci using Fig. 4. The input power, field current, total power lost, efficiency, etc., are then given by the various loci lines passing through the operating point, using diagrams such as Figs. 4 and 5.

Conclusion

The principles presented in this paper have been put to laboratory test[4] as far as the university facilities allow and satisfactory agreement of theoretical and experimental results was found in all cases.

3. For example, see John I. Hull, *Theory of Speed and Power Factor Control of Large Induction Motors by Neutralized Polyphase A-C. Commutator Machines*, A. I. E. E. Trans., Vol. 39, 1920, p. 1135.

4. The results are to be found in the following Stanford University theses: T. L. Lenzen and K. A. Rogers, *Application of the Transmission Line Circle Diagram to Transformers and Alternators;* C. L. Freedman, *Application of the Transmission Line Circle Diagram to the Induction Motor*.

The circle diagram of a transmission network, developed to solve transmission line problems, seems to be the fundamental circle diagram, applying to many varieties of electrical circuits and machinery. Its use in connection with transformers and synchronous motors, generators, and condensers leads to circle diagrams fully as useful as the classical induction motor diagram.

The authors wish to express their appreciation for the assistance rendered by Mr. Monges of the General Electric Company in supplying data on commercial equipment.

Appendix I

Determination of Network Constants by Measurement

Direct Measurement of A. From Equation (1) it is seen that with the receiver open:

$$A = E_s/E_r \qquad (8)$$

The vector ratio E_s/E_r can be measured in both magnitude and phase by the three-voltmeter method, or by successive applications of the three-voltmeter method. The phase can also be measured by a wattmeter in which the current in each of the coils is proportional to one of the two voltages.

Direct Measurement of B. From Equation (1) it is seen that with the receiver terminals short circuited:

$$B = E_s/I_r \qquad (9)$$

The phase of B can be determined by the use of a wattmeter in which E_s is applied to the voltage coil and I_r flows through the current coil.

Measurement of C. From Equation (1) it is seen that when the receiver terminals are open circuited:

$$C = I_s/E_r \qquad (10)$$

This vector ratio can be readily obtained by the use of ammeter, voltmeter, and wattmeter.

Measurement of D. With power supplied at the receiver terminals, and with the sending end terminal open, Equation (2) shows:

$$D = E_r/E_s \qquad (11)$$

Measurement of Constants When Both Ends of Network are not Available at One Point. An example of this is a transmission line. Since there are three independent network constants any three independent measurements are sufficient. The measurements most easily made are:

(1) Sending end impedance Z_1 with receiver open.
(2) Sending end impedance Z_2 with receiver shorted.
(3) Impedance Z_3 at receiver with sending end open.
(4) Impedance Z_4 at receiver with sending end shorted.

According to Equations (1) and (2) these impedances are related to the network constants as follows:

$$\begin{aligned} Z_1 &= A/C \\ Z_2 &= B/D \\ Z_3 &= D/C \\ Z_4 &= B/A \end{aligned} \qquad (12)$$

The simultaneous solution of any three of these four equations together with the relation $A\,D = 1 + B\,C$ will enable the four network constants to be computed. The four equations of (12) cannot be simultaneously solved themselves to give the four network constants because only three of these constants are independent.

Appendix II

Approximate Method of Computing Loss Radii

Reference to a previous article[2] shows that loss circle radii are given by an equation of the form

$$\text{Radius} = m\sqrt{L - L_0}$$

where m and L_0 are constants that can be computed from the network constants and the terminal voltage. In these computations, however, L_0 is difficult to determine accurately as it is the small difference of two nearly equal quantities.

In the case of equipment such as the transformer, alternator, etc., where the minimum possible loss with the fixed terminal voltage is for all practical purposes the no-load loss, it is permissible to substitute the no-load losses for the quantity L_0. This is because the loss L_0 is the minimum possible loss with the fixed terminal voltage being used. With this simplification the loss radii may be easily computed with satisfactory accuracy.

Effect of Electric Shock

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Synopsis.—This paper describes an investigation of the effects of electric shock on the central nervous system. A total of 286 rats was employed in the investigation. These were shocked at 110, 220, 500, and 1000 volts on both alternating and continuous current circuits for varying lengths of time. In each series the duration of the shock was increased until it was found impossible to resuscitate the rats. When possible the rats were resuscitated by means of artificial respiration, and kept alive for about a week. Then they were killed by an overdose of ether and an autopsy was immediately made.

The rats reacted in entirely different manner on the two types of circuit. At the lower voltages the alternating current was deadlier than the continuous, but at the high voltage the opposite was found to be the case.

In many instances the rats were paralyzed by the application of the current and in the majority of these animals gross hemorrhages were found in the spinal cord at autopsy. All of the deaths that occurred as a result of the shock were caused by respiratory failure, which could usually be traced to an injury of the central nervous system. In some cases the electric current produced peculiar effects upon the rats.

* * * * *

General

THE first death from contact with an electric circuit occurred in France in 1879. As the use of electricity has become prevalent the number of deaths has also increased; at present the death rate from electricity in the United States is 0.9 per 100,000, in Switzerland 0.7 per 100,000, and in England and Wales 0.07 per 100,000. There has been less development of the electric industry in England and Wales and this no doubt accounts for their lower death rate. The number of deaths from electricity in the United States has kept pace with the growth in population but is not increasing as fast as the use of electricity is being extended. Approximately 50 per cent of the accidents in this country are fatal. The injuries occur with greatest frequency between 9 and 10 in the morning and 2 and 3 in the afternoon. Recently there seems to be a definite increase in the number of deaths caused by contact with low-voltage circuits such as are used in residences.

In the case of an electric accident there are five factors that are of importance for investigation, namely:

1. The voltage of the circuit.
2. The amount of current that flows through the body.
3. The duration of the contact.
4. The type of circuit, direct or alternating, and the frequency.
5. The points on the body where contact is made with the circuit.

Voltage

It is a well recognized fact that high voltages are dangerous. Low voltages are also dangerous and especially so when the victim makes good contact. There is an authentic case in Italy of a man who was electrocuted on a 46-volt circuit, one in Vienna on 60 volts, and one in England on 65 volts. All of these accidents took place on alternating systems. Deaths on 110-volt a-c. circuits are becoming quite common as already mentioned. It has not been possible to find any record of a fatal accident on a 110-volt continuous current system. Approximately one-third of the fatal accidents reported, occur on low-voltage a-c. circuits.

On high-voltage circuits the victim is often thrown away from the conductors due to the severe contraction of the muscles. On low voltage it is often impossible to let go.

Current

The current that will flow in any given instance depends not only upon the voltage of the circuit, but also upon the resistance offered by the body. The determination of the resistance of the body is a very complex problem. There is a voltage drop at the contacts in addition to the resistance drop in the body itself. Dry skin on the palm of the hand has a resistance which varies from 40,000 ohms to 100,000 ohms per sq. cm. Blood is a good conductor and the subcutaneous tissue being rich in blood vessels is therefore a good conductor. The resistance of muscle is of the order of 1500 ohms per cu. cm., the brain 2000 ohms, the liver 900 ohms, and that of bone 900,000 ohms. It is evident that the major part of the resistance that the body offers to the flow of electric current lies in the contacts with the skin. When the skin is thoroughly wet its resistance falls to about 1000 ohms. When the contacts are excellent, as at Sing Sing, the resistance offered by the victim falls to nearly 200 ohms.

The sensation produced by an alternating current of 18 to 20 milliamperes is painful and currents of 100 milliamperes are dangerous and may cause death. It is therefore quite evident that 110-volt circuits are dangerous if the skin of the victim is wet.

The resistance of the body decreases if contact is made with an electric circuit for any length of time. In the experiments on animals it was found that the current increased 5 to 10 per cent if the animal was allowed to remain in the circuit for any length of time.

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There was also a rise in temperature as determined by rectal thermometer.

Duration of Contact

The possibility of successful resuscitation decreases rapidly as the time of contact with the circuit increases. The higher the voltage of the circuit, the shorter the time that a man can remain in contact with it and still be resuscitated.

Type of Circuit

Low-voltage a-c. systems of commercial frequency are more dangerous than continuous current circuits of the same voltage. A continuous current produces electrolysis of the body fluids and some strong contractions of the muscles. Alternating current, on the other hand, produces no electrolysis but a very severe contraction of the muscles.

Position of the Electrodes

If the contact of the body with the circuit occurs at points so located that the current does not pass through any vital organ no permanent damage as a rule will result.

Effects of Electric Shock

Jex-Blake[2] in his Gulstonian Lectures discussed at some length the injuries produced by electricity and more recently Jaffe[1] has published a review of this whole subject. Only a few of the effects of electric shock will be discussed here and the reader is referred to the original articles for a more complete study of the subject and for other references.

One of the most common effects of the passage of an electric current through the body is a burning of the skin. The skin receives a negative of the conductor with which it makes contact. Severe electric burns usually are slow in healing and leave a thin pinkish scar.

The passage of the current through the body produces a severe continuous contraction of the muscles or tetanus as it is called. The walls of the blood vessels through which the current has passed are brittle and friable and this accounts for the severe hemorrhages that are often found following electrical accidents. The blood contains an increased number of white corpuscles after the passage of an electric current.

When a low-tension current passes through the heart of animals uncoordinated contractions of the separate muscle fibers of the ventricles of the heart take place. This is called fibrillation and it is produced by the direct action of the current on the muscle fibers of the heart. It is not believed that the heart of man or of the larger animals ever recovers spontaneously from fibrillation. Perhaps a counter shock will combat the fibrillation, but there are few data available on this subject. When a high-tension current is applied the heart stops immediately, on breaking the circuit it starts to beat rapidly and strongly and the blood pressure rises. Injury to the heart is believed therefore to be more common at low voltage and this is perhaps one of the reasons that more people are resuscitated after contacts with high-voltage circuits than with low-voltage circuits.

1. For numbered references see Bibliography.

Exposure to circuits of 550 volts and higher gives a number of indications that the central nervous system is involved. These are the arrest of respiration, irregular respiration, clonic spasms, loss of sensation, loss of reflexes, and great prostration which may pass into a deep coma. Jaeger[3] states that an electric shock is similar to a concussion of the brain.

The possible causes of death are:

1. Prolonged tetanus of the muscles during passage of the current, producing exceedingly high temperatures or death from asphyxia.
2. Heart failure usually associated with ventricular fibrillation.
3. Respiratory failure through nervous inhibition or actual damage to nervous system; and
4. Burns or other complications.

Death usually centers around the paralysis of the heart or of the respiratory centers.

Experimental Study

The purpose of this investigation was to determine the effect of an electric shock upon the central nervous system, to study the behavior of shocked animals, to ascertain if possible the cause of deaths due to respiratory failure, and to find how many cases of delayed deaths are the result of demonstrable lesions in the central nervous system.

In studying the effects of electric shock two methods are available, the study of accidents or animal experimentation. The study of accidental deaths is difficult because of lack of accurate knowledge of all the factors involved, and the long delay before performing autopsies.

The sensibility to an electric current varies greatly with different animals. Frogs and turtles are the most resistant, rats and rabbits come next in the scale, and dogs and horses are very easily killed. Rats were chosen for this investigation because they are easy to transport and inexpensive. The heart of a rat recovers spontaneously from fibrillation and in the present tests there were no deaths from either prolonged tetanus of the muscles or heart failure.

The effect on rats of alternating and continuous currents at potentials of 110, 220, 500, and 1000 volts for varying lengths of time was studied. The authors felt that the changes in the nerve cells could be seen especially clearly if the animal was resuscitated after the shock and allowed to live several days. This procedure was carried out, the rat was then killed and the central nervous system examined at once. Attention was confined mainly to a study of the effects produced by the electric current on the spinal cord and brain.

These experiments were made at constant supply voltage, which was maintained except in the preliminary tests as mentioned below. Constant voltages were

chosen rather than constant currents because they correspond to standard practise. In the case of an accidental death on a circuit the voltage applied to the victim is usually known quite accurately, but there are few or no data as to the amount of current that passed through his body.

It must be remembered that the results obtained from a study of one experimental animal cannot be directly applied to a consideration of other animals or of man. It is expected that the pathological changes in the central nervous system, the study of which formed the main object of this investigation, will be found similar in all mammals.

Current Supply

The 110- and 220-volt alternating and continuous current supplies were taken directly from the Electrical Engineering Laboratory circuits. The 500- and 1000-volt a-c. voltages were furnished by a 1 to 10 step-up transformer, in which primary voltage was furnished by a separate alternator whose voltage controlled by means of a field regulation. The 500- and 1000-volt continuous current voltages were furnished by a separately excited 800-volt continuous current generator. A switch was placed in the high-tension circuit in which the rat was connected, and this switch was used to close the circuit. The frequency of the alternating current was 60 cycles.

In the first test at 500 and 1000 volts alternating current the primary voltage feeding the step-up transformer was furnished from the laboratory circuit and controlled by a potentiometer type of rheostat. The amount of current taken by the animals was larger than anticipated and there resulted a considerable fall in voltage due to the drop in the rheostat. Measurements showed that in the case of the 500-volt preliminary tests, the voltage felt to approximately 100 volts and in the preliminary 1000-volt series to 220 volts. The actual values varied with the size of the animals. This method of connection was abandoned and the primary voltage controlled by means of the alternator field as described above. Nevertheless the results of the observations made on the circuit in which the voltage fell upon closing the switch to about 20 per cent of its initial value are very interesting, because they show that the initial shock plays a large part in the injury to the animal.

The current flowing through the rat was measured by means of the proper range and type of ammeter.

Technique

While the animal was being given ether the voltage was adjusted to the desired value for the test. As soon as the rat was anesthetized the electrodes were attached after wetting the skin with a saturated salt solution. One electrode, two voltmeter clips filed smooth, was fastened to the base of the tail, and the other electrode placed on the skull. The electrode, used on the skull, was especially made for the work and was held in place by springs that pressed against the lower jaw and did not in any way obstruct the breathing. The electrode proper was 1.2 cm. in diameter and was insulated from the springs so that all of the current passed through the top of the head.

In the majority of tests the electrodes were applied on the head and tail of the rats as described above. Another group of observations was made with one electrode on the head and the other on one of the fore legs and also with one electrode on one fore leg and the other on the opposite hind leg. The results obtained were similar and apparently entirely independent of the electrode positions.

After the electrodes were in position the animal was closely watched until it showed signs of initial recovery from the ether; then the high-tension switch was closed for the proper length of time. Immediately following the opening of the circuit the electrodes were removed from the animal and artificial respiration was applied. If possible the rat was resuscitated and allowed to live for three or four days. It was then killed and an autopsy performed at once.

In addition to the findings at autopsy the authors have made sections of the central nervous systems of the animals. The preparation and study of the sections requires considerable time and a further report will embody these findings. It is hoped that these microscopic data will furnish considerable information concerning the cause of the abnormalities seen in the rats after the shock.

The resuscitation method used was as similar as possible to the Schaefer prone-pressure method used for man. Every effort was made to save the rat and often artificial respiration was continued for 10 or 15 minutes. In the case of those animals which died under shock, and which could not be induced to breathe, autopsies were performed at once.

The circuit was held closed for varying lengths of time, the shortest interval, called instantaneous time, being just sufficient to close and open the switch. The duration of the shock was measured by means of a stop watch. In making the tests at any given voltage a shock of short duration was used for the first experiments and gradually increased until it was no longer possible to resuscitate the animal.

Observations

The experiments described in this paper are 286 in number and include groups of rats shocked on alternating and continuous circuits at different potentials. The results of these observations may be grouped and examined in a number of different ways. After studying them from several different points of view it was decided best to describe the results obtained with alternating and continuous circuits using in each case four potentials of 110, 220, 500, and 1000 volts. With each potential and circuit, rather characteristic results of the shock were obtained. The time that the current was

allowed to flow through the body was varied in the different experiments in each series. In general the time was longest with the lower voltages. The different experiments will first be described in groups or series on the basis of the potential and the type of circuit, and later these series will be compared.

The results are given in the form of tables and the data on the rats shocked at a given voltage for a certain interval of time are arranged in the order of the currents that flowed through the animal.

110 Volts Alternating Series. Eleven rats were shocked at this voltage; the time of contact varied from 10 to 30 seconds. The results are given in Table I. The average resistance was 3091 ohms. Of the eleven rats of this series, seven, 64 per cent recovered; three, 27 per cent died, and one, 9 per cent, was paralyzed. When the paralyzed rat was examined blood was found in the urine and a large hemorrhage in the spinal cord. Hemorrhages of this type in the spinal cord were found often as a result of the shock.

As may be seen from Table I, artificial respiration was used on all but one of the rats. Their recovery was slow and they lay quiet from a few minutes to half an hour following the shock. They were inactive for the first 24 hours and did not eat or drink; after that period they became apparently normal.

One of the rats that recovered, No. 8, died three hours later, and upon autopsy was found to have a large hemorrhage in the spinal cord. One of the three rats that died at once was found to have a hemorrhage in the cord, but the other two showed no gross abnormalities.

Of the six rats that recovered and continued to live, until killed, five were found to be normal and one showed a hemorrhage in the brain.

Three of the rats, Nos. 9, 10, and 11, that were in the circuit for some time breathed spontaneously while the circuit was closed. They all stopped breathing when the circuit was opened; two were saved by artificial respiration, and the third never breathed again although the heart was strong.

Two of the rats that recovered had spasms of the muscles and in two cases bleeding from the nose was evident, caused by the rupture of the small blood vessels.

In summary, 45 per cent of the rats died or were permanently injured as a result of the shock on a 110-volt alternating circuit.

220 Volts Alternating Series. Twenty-nine rats were shocked at this voltage; the time of contact varied from 5 to 35 seconds. The results are given in Table II. The average resistance was found to be 1890 ohms, and the currents varied from 80 to 200 milliamperes. Of the 29 tested, eight, 28 per cent, recovered; eleven, 34 per cent, died; and ten, 38 per cent, were paralyzed. The ten that were paralyzed became incontinent (could not control the bladder). All showed blood in the urine, and all showed typical hemorrhages in the spinal cord.

It was necessary to use artificial respiration on all but two of the rats. Their recovery was slow and their breathing was shallow, labored, and irregular.

Seven, of the eleven that died, started to breathe with artificial respiration, but the breathing was not maintained and they died despite efforts to save them. One of the four that never started to breathe, rat No. 29, was kept in the circuit for 35 seconds and during that time the current increased from an initial value of 80 milliamperes to 166 milliamperes, and its rectal temperature rose from 36.5 deg. cent. to 38 deg. cent. In the case of all of the rats that were held in the circuit for several seconds there was an increase in current with time.

Of the eleven rats that died, three showed a developing hemorrhage in the spinal cord and one a hemorrhage in the brain. The others were normal as far as could be detected at autopsy. One of the eight that recovered showed a slight hemorrhage in the cord.

A study of Table II shows several instances marked "No specimen." This indicates that either the rat managed to free himself of a little aluminum tag carrying his identification number or that no autopsy was performed directly after death.

The chances of injury or death from contact with an electric circuit decreases with the length of time of the contact. This is clearly brought out by the data in Table II; one-half of the eleven rats tested at contact durations of five to eight seconds recovered, but only 13 per cent of the rats shocked for ten seconds recovered.

An interesting point is brought out by the results of

TABLE I
110-VOLT A-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage: Brain	Gross hemorrhage: Cord	Sex	Wt. gr.
1	10	....	Yes	Recovered	Normal	Normal	....	....
2	10	26.5	Yes	Died	Normal	Normal	....	....
3	10	38	Yes	Paralyzed	Normal	Yes	....	....
4	10	40	Yes	Died	Normal	Normal	....	....
5	14	25	Yes	Recovered	Yes	Normal	....	....
6	14	33.5	No	Recovered	Normal	Normal	....	....
7	18	47	Yes	Recovered	Normal	Normal	....	....
8	22	47.5	Yes	Recovered	Normal	Yes	....	....
9	26	40	Yes	Recovered	Normal	Normal	....	Large
10	30	30	Yes	Died	Normal	Yes	....	Very large
11	30	47	Yes	Recovered	Normal	Normal	....	....

TABLE II

220 VOLT A-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage		Sex	Wt.
					Brain	Cord		
1	5	..	No	Recovered	Normal	Normal	F	240
2	5	100	Yes	Paralyzed	No specimen		M	160
3	5	110	No	Paralyzed	Normal	Yes	..	..
4	5	135	Yes	Recovered	Normal	Normal	M	150
5	6	110	Yes	Paralyzed	Normal	Yes	M	120
6	8	105	Yes	Died	Normal	Normal	M	140
7	8	110	Yes	Recovered	No specimen		M	160
8	8	120	Yes	Recovered	Normal	Normal	M	150
9	8	120	Yes	Paralyzed	No specimen		F	140
10	8	140	Yes	Recovered	Normal	Yes	F	110
11	8	140	Yes	Paralyzed	Normal	Yes	F	200
12	10	80	Yes	Died	Normal	Yes	..	..
13	10	80	Yes	Died	Normal	Normal	..	..
14	10	90	Yes	Paralyzed	Normal	Yes	M	210
15	10	100	Yes	Paralyzed	No specimen		M	100
16	10	120	Yes	Died	Yes	Normal	..	190
17	10	125	Yes	Paralyzed	Normal	Yes	M	160
18	10	130	Yes	Paralyzed	No specimen		M	210
19	10	140	Yes	Recovered	Normal	Normal	M	170
20	12	100	Yes	Died	Normal	Normal	M	140
21	12	120	Yes	Died	Normal	Normal	M	180
22	12	160	Yes	Paralyzed	Normal	Yes	M	260
23	14	100	Yes	Died	Normal	Normal	F	180
24	14	150	Yes	Recovered	Normal	Normal	M	270
25	14	150	Yes	Died	Normal	Normal	M	230'
26	14	150	Yes	Died	Normal	Yes	F	200
27	14	170	Yes	Recovered	Normal	Normal	M	250
28	14	200	Yes	Died	Normal	Normal	F	180
29	35	80	Yes	Died	Normal	Yes	..	..

a 14-second shock; the two rats that recovered from this shock were both very large. It was found that the small rats succumb much more easily to electric shock than the larger animals. It is believed that this is due to the lower current density in the vital organs of the larger animals.

No differences were found between the death rates of the two sexes. Pregnant females, however, are very easily killed by contact of short duration.

Twenty-two of the rats used in this series bled from the nose or eyes. One peculiar phenomenon, for which no explanation is known, is that in case of bleeding from the eyes the right eye bled more often than the left. In the case of one of the males there was an ejaculation.

The percentage of rats that were permanently injured or died on the 220-volt circuit was 72. This greater percentage of injuries in combination with the short time of application indicates clearly that 220 volts is much more deadly to rats than 110 volts.

500-Volt A-C. Series. Twenty-six rats were shocked at this voltage; the time of contact was varied from 1 to 4 seconds. The detailed results are given in Table III. Of the 26 tests, ten, 38 per cent recovered; three, 12 per cent died, and thirteen, 50 per cent were paralyzed. All of the paralyzed rats, except one, showed the typical hemorrhage in the spinal cord. The average ohmic resistance of the rats was 1425 ohms, and the current varied from 240 to 490 milliamperes.

An inspection of Table III will show that a number of rats on this circuit recovered spontaneously after the circuit was opened. As the time of the contact was increased, artificial respiration became necessary. The contraction of the muscles upon the closing of the circuit was very great, the legs were stiffly extended, and the contraction persisted for several seconds after opening the circuit. There were clonic movements and tremors following the opening of the circuit. Eighteen of the animals bled from the nose or eyes following the shock.

Not a single animal survived a four-second application without permanent injury. In the paralyzed rats that were examined the typical hemorrhage in the spinal cord was found in all except rat 24. In one, of the three that died, the surface of the cortex was found to be seared, in another there was a hemorrhage in the brain. One was apparently normal.

There was some burning at the points where the electrodes were fastened to the animal in four of the rats. Bleeding from eyes or nose or both was observed in 18 cases, and in three of the rats there was a discharge of bloody fluid from the mouth. Ejaculation was noticed in the case of four of the six males that were shocked for periods of 3 and 4 seconds. In one of the ten rats that recovered there was a slight hemorrhage in the brain; the others appeared normal.

This series also clearly demonstrated that there is no difference between the susceptibility of the sexes to electric shock. It is evident that an application of 500 volts is much more injurious than the lower voltages; with a maximum time of application of four seconds, 62 per cent of the animals were paralyzed or died.

1000 Volts Alternating Series. Twenty-eight rats were subjected to a potential of 1000 volts for periods varying from one to four seconds. The results are given in Table IV. The average resistance was found

TABLE III
500 VOLTS A-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage: Brain	Gross hemorrhage: Cord	Sex	Wt. gr.	Remarks
1	1	....	Yes	Recovered	Normal	Normal	F	280	
2	1	300	No	Recovered	Normal	Normal	M	180	
3	1	305	No	Recovered	Normal	Normal	M	230	
4	1	340	Yes	Recovered	Normal	Normal	M	180	
5	1	380	No	Paralyzed	No specimen		M	140	
6	1	395	Yes	Paralyzed	No specimen		F	170	
7	2	240	Yes	Recovered	Yes	Normal	..	..	
8	2	250	No	Recovered	No specimen		M	220	
9	2	350	Yes	Paralyzed	No specimen		F	170	
10	2	360	No	Recovered	Normal	Normal	F	210	
11	2	380	No	Paralyzed	Normal	Yes	F	180	
12	2	385	No	Recovered	Normal	Normal	F	180	
13	2	400	Yes	Paralyzed	No specimen		F	100	
14	3	280	Yes	Died	Normal	Yes	..	..	
15	3	360	Yes	Recovered	Normal	Normal	F	200	
16	3	380	Yes	Died	Normal	Normal	M	150	
17	3	400	Yes	Paralyzed	No specimen		M	210	
18	3	400	Yes	Paralyzed	No specimen		M	260	
19	3	430	Yes	Recovered	Normal	Normal	F	210	
20	3	430	Yes	Paralyzed	Normal	Yes	F	280	
21	3	490	Yes	Paralyzed	No specimen		M	250	
22	4	280	Yes	Paralyzed	Normal	Yes	F	180	
23	4	340	Yes	Paralyzed	Normal	....	M	210	
24	4	350	Yes	Died	....	Normal	F	350	Cortex burned
25	4	400	Yes	Paralyzed	Normal	Yes	F	200	
26	4	430	Yes	Paralyzed	No specimen		M	220	

to be 1140 ohms, and the current varied from 700 to 1200 milliamperes. Of those tested, eight, 29 per cent recovered; nine, 32 per cent, died, and eleven, 39 per cent, were paralyzed. The ten that were paralyzed all became incontinent, blood was found in the urine, and all except one showed the typical spinal hemorrhage.

It was necessary to use artificial respiration on nearly every rat and in many cases considerable effort for a prolonged period was required to save the animals. In some cases, breathing was started by means of artificial respiration, only to stop again. Then artificial respiration had to be applied anew. In a few cases it was necessary to watch the animals for half an hour or more. Some died despite every effort. In those that lived the breathing was shallow, irregular, and labored.

The contraction of the muscles was very great and it persisted for several seconds after the circuit was opened. Clonic movements and tremors also followed the opening of the circuit. Many of the rats exhibited spas-

TABLE IV
1000-VOLT A-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage: Brain	Gross hemorrhage: Cord	Sex	Wt. gr.	Remarks
1	1	....	Yes	Died	Yes	Normal	F	90	
2	1	....	Yes	Paralyzed	Normal	Yes	M	160	Cortex burned
3	1	680	Yes	Paralyzed	No specimen		M	140	
4	1	700	Yes	Paralyzed	Normal	Normal	M	170	
5	1	720	No	Recovered	Normal	Normal	M	160	
6	1	800	No	Paralyzed	Normal	Yes	M	160	
7	1	1000	Yes	Recovered	Normal	Normal	F	110	
8	2	....	No	Paralyzed	Normal	Yes	..	..	
9	2	....	Yes	Paralyzed	Normal	Yes	F	230	
10	2	650	Yes	Paralyzed	Normal	Yes	..	..	
11	2	800	Yes	Recovered	No specimen		F	190	
12	2	830	No	Paralyzed	Normal	Yes	F	230	Skull injured
13	2	900	Yes	Recovered	....	Normal	F	240	Abscess brain
14	2	950	Yes	Died	....	Normal	M	200	Cortex burned
15	2	980	Yes	Paralyzed	Normal	Yes	F	270	
16	2	1000	Yes	Died	....	Normal	F	180	Cortex burned
17	2	1000	Yes	Recovered	....	Normal	F	210	Cortex burned
18	3	770	Yes	Died	Normal	Yes	..	..	
19	3	800	Yes	Died	Normal	Normal	..	..	
20	3	820	Yes	Recovered	No specimen		M	290	
21	3	840	Yes	Died	Normal	Yes	F	280	
22	3	850	Yes	Paralyzed	Normal	Yes	F	290	
23	3	890	Yes	Died	....	Normal	F	230	Cortex burned
24	3	980	Yes	Recovered	Normal	Yes	M	390	Skull injured
25	3	1060	Yes	Paralyzed	Normal	Yes	M	320	
26	3	1200	Yes	Died	....	Normal	F	..	Cortex burned
27	3	1250	Yes	Recovered	Normal	Yes	M	380	
28	4	1200	Yes	Died	Normal	Normal	M	350	

modic contractions of the muscles of mastication. Twelve bled from the nose or eyes or both.

Of the nine rats that died, seven showed injuries to the spinal cord or brain, and two were apparently normal. It was possible to start respirations in several of these animals, but breathing could not be maintained. In all nine cases the heart beat strongly after the shock.

There was severe burning at the electrode contact and several of the rats that recovered subsequently showed severe injuries from this cause.

A study of Table IV will show that many of the rats used in this series were of large size. This to some extent accounts for the fact that there was not a greater mortality. The results show that 71 per cent died or were paralyzed. The large size of the rats also accounts for the low average resistance, and large values of current found for this series.

500 Volts Alternating Not Maintained Series. Sixteen rats were shocked for periods varying from instantaneous contact to 14 seconds. The voltage fell to approximately 100 volts upon closing the switch. An oscillogram of the voltage in the high-tension circuit showed that it fell to its final low value in less than one-fourth a cycle. The final maintained current varied from 20 to 30 milliamperes. Of the 16 experimental animals, eleven, 69 per cent, recovered and five, 31 per cent, were paralyzed. Autopsy showed that four of the paralyzed rats had the typical hemorrhage of the spinal cord and one was apparently normal.

The contraction of the muscles was great and clonic movements followed the opening of the circuit. Artificial respiration was applied to four and in almost every case the breathing was shallow and irregular.

Of the eleven that recovered, no autopsy was performed on one rat; one showed a developing hemorrhage in the brain and cord, and the other nine were apparently normal.

It is interesting to note that, although the voltage was not maintained, a number of rats was paralyzed after contact with this circuit. This contact, however, did not produce as severe injuries as the 500-volt a-c. maintained voltage circuit.

1000 Volts-Alternating Not Maintained Series. Fifty-two rats were shocked in this series; the time was varied from instantaneous contact to six seconds. After closing the circuit the voltage fell to approximately 220 volts in less than a quarter of a cycle as shown by an oscillogram. The final maintained current varied from 98 to 155 milliamperes. Of the number tested, twelve, 23 per cent, recovered; twenty-four, 46 per cent, died, and sixteen, 31 per cent, were paralyzed. Thirteen of the sixteen paralyzed rats showed gross hemorrhages in the spinal cords, one showed a hemorrhage in the brain, and on the other two no autopsies were performed.

It was necessary to use artificial respiration on 31 per cent of the rats in this series, but it was not necessary to continue it as long as in the experiments where the voltage had been maintained at 1000 volts. Breathing, however, was shallow, irregular, and labored for a considerable time following the shock.

The contraction of the muscles was severe and clonic movements followed the opening of the circuit; three rats bled from the nose following the shock.

Of the twelve that recovered eleven were normal, and one showed signs of a hemorrhage in the cord.

The results of this series show that 77 per cent of the rats were either permanently injured or killed by contact with this circuit where the voltage was at its full value for only a very short time. This points to the conclusion that the hemorrhages in the spinal cord are largely the result of the first contact with the circuit. This contact was very nearly as injurious to the rats as the 1000-volt alternating circuit where the voltage was maintained.

110-Volt Continuous Series. Thirty-three rats were subjected to this voltage; the duration of the shock varied from 5 to 60 seconds. The results are given in Table V. The average resistance equaled 2685 ohms and the current varied from 28 to 53 milliamperes. Of the number observed twenty-eight, 85 per cent, recovered, four, 12 per cent, died, and one, 3 per cent, was paralyzed. The paralyzed rat showed the typical hemorrhage in the spinal cord which was so commonly found in rats shocked on a-c. circuits.

During the passage of the current the contraction of the muscles was not as great as on an a-c. circuit of the same voltage. During long time applications the current increased as it did in the alternating cases. There were clonic contractions of the muscles during the passage of the current. No artificial respiration was needed in the case of those rats which were held in circuit less than 20 seconds; they started to breathe spontaneously. If the rat was held in the circuit for more than 20 seconds it began to breathe while the current was still flowing. When the circuit was opened breathing stopped and it was usually necessary to apply artificial respiration to start the animal breathing again. The rats recovered promptly and were active sooner than those which had been given a shock with 110-volt alternating current. There was no evidence of bleeding in this series.

One of the four rats that succumbed to the shock was found to have a hemorrhage in the brain; the other three showed no abnormalities at autopsy. In two of the rats that recovered, hemorrhages were found; the others examined were normal. The heart beat well following the shock in all cases.

Only 15 per cent of the rats tested on a 110-volt continuous circuit were injured or died, although the duration of the shock was considerably longer than in the 110-volt alternating series.

220 Volts Continuous Series. Nineteen rats were shocked at 220 volts continuous potential; the duration of the shock varied from 5 to 30 seconds. The detailed

results are given in Table VI. The average resistance equaled 1635 ohms and the current varied from 100 to 200 milliamperes. Of the rats tested at this voltage ten, 53 per cent, recovered, eight, 42 per cent, died; and one, 5 per cent, was paralyzed. No sign of any gross abnormality could be detected on examination after death in the paralyzed rat.

In this group it was again noted that the muscle contraction was less than on an alternating circuit; the animals were more relaxed after the shock. Clonic movements were present in all of these rats both during and immediately following the shock. It was necessary to use artificial respiration on all but five of the rats in this series, and none of them breathed while in the circuit. No bleeding was noticed in this series.

Of the eight rats that died, one was found to have a hemorrhage in the brain; the others that were examined were normal. None of the rats that recovered showed abnormalities in either the spinal cord or brain. In this series 47 per cent of the rats died or were injured.

TABLE V
110-VOLT D-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage		Sex
					Brain	Cord	
1	5	..	No	Paralyzed	Normal	Yes	..
2	5	28	No	Recovered	No specimen		..
3	5	38	No	Recovered	No specimen		..
4	10	35	No	Recovered	No specimen		..
5	10	40	No	Recovered	Normal	Normal	..
6	10	40	No	Recovered	Normal	Normal	..
7	10	44	No	Recovered	Normal	Normal	..
8	14	39	No	Recovered	No specimen		..
9	14	46	No	Recovered	No specimen		..
10	15	40	No	Recovered	Normal	Yes	..
11	20	42	No	Recovered	Normal	Normal	..
12	20	44	Yes	Died	Normal	Normal	..
13	22	42	Yes	Recovered	Normal	Nomral	..
14	22	53	Yes	Recovered	Normal	Normal	..
15	25	30	No	Recovered	Normal	Normal	..
16	26	41	No	Recovered	No specimen		F
17	28	40	No	Recovered	Normal	Normal	..
18	30	36	No	Recovered	Yes	Normal	F
19	30	48	Yes	Recovered	No specimen		M
20	30	50	Yes	Recovered	Normal	Normal	..
21	35	35	No	Revoereed	Normal	Normal	M
22	35	47	Yes	Recovered	Normal	Normal	F
23	35	50	Yes	Recovered	No specimen		M
24	40	32	No	Recovered	No specimen		M
25	40	41	Yes	Recovered	Normal	Normal	M
26	45	40	No	Died	Yes	Normal	M
27	45	43	No	Recovered	Normal	Normal	M
28	50	36	No	Recovered	Normal	Normal	M
29	50	34	No	Recovered	Normal	Normal	M
30	50	36	No	Died	Normal	Normal	M
31	50	47	No	Recovered	Normal	Normal	M
32	60	37	Yes	Recovered	Normal	Normal	..
33	60	47	Yes	Died	Normal	Normal	M

TABLE VI
220-VOLT D-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage	
					Brain	Cord
1	5	100	No	Recovered	Normal	Normal
2	5	145	Yes	Recovered	Normal	Normal
3	5	170	No	Recovered	Normal	Normal
4	10	145	Yes	Recovered	Normal	Normal
5	10	195	Yes	Paralyzed	Normal	Normal
6	10	200	Yes	Recovered	Normal	Normal
7	15	135	No	Recovered	Normal	Normal
8	15	135	Yes	Died	Normal	Normal
9	15	140	Yes	Died	Yes	Normal
10	15	155	Yes	Recovered	Normal	Normal
11	15	155	Yes	Died	No specimen	
12	15	175	Yes	Died	Normal	Normal
13	15	250	Yes.	Died	No specimen	
14	20	120	Yes	Died	Normal	Normal
15	20	200	Yes	Recovered	Normal	Normal
16	25	115	No	Recovered	Normal	Normal
17	30	100	No	Recovered	Normal	Normal
18	30	150	Yes	Died	No specimen	
19	30	155	Yes	Died	Normal	Normal

500-Volt Continuous Series. Thirty-seven rats were shocked at this voltage; the duration of the shock varied from 1 to 4 seconds. The results in detail are given in Table VII. The average resistance was 1385 ohms; the current varied from 280 to 640 milliamperes. Eighteen, 49 per cent, of the thirty-seven recovered; seventeen, 46 per cent, died; and two, 5 per cent, were paralyzed. No trace of hemorrhage in the nervous system could be found in the two paralyzed rats at autopsy.

The contraction of the body musculature was not as severe as on an alternating circuit. Clonic movements were noticed both while the current was flowing and after the circuit was opened. Artificial respiration was needed in all except four cases, and the heart beat well in all of the rats for four or five minutes after the shock. Five of these rats had convulsions following the shock and showed increased and abnormal responses to all stimuli. This was the only series in which these convulsions were observed. Ten of the animals bled from the nose, eyes, or mouth, and it will be noted that this is the first appearance in the continuous current series of this phenomenon which was so common in the alternating groups.

No apparent injury to the nervous system on gross examination could be detected in any of the eighteen rats that died. Only two of the rats in this series showed hemorrhages in the brain, and these two rats recovered from the shock. All of the recovered rats were normal; their breathing, however, was labored and fast.

This series brings out clearly the effect of the size of the animal upon the experimental results. Eleven rats, three months old, were given a two-second shock and seven of them died. Of four larger rats under the same duration of shock two died, and two recovered. The results of three-second application, as may be seen from Table VII, also confirms this conclusion as to the effect of size of the animal upon the results.

TABLE VII
500 VOLTS D-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage Brain	Gross hemorrhage Cord	Sex	Wt.
1	1	280	No	Recovered	Yes	Normal	F	Small
2	1	300	No	Recovered	Normal	Normal	M	Small
3	1	300	Yes	Recovered	Normal	Normal	F	Small
4	1	300	Yes	Recovered	Normal	Normal	F	Small
5	1	300	Yes	Died	Normal	Normal	F	Small
6	1	320	No	Recovered	Normal	Normal	F	Small
7	1	370	Yes	Recovered	Normal	Normal	M	Small
8	1	390	Yes	Recovered	Normal	Normal	F	Small
9	2	270	Yes	Recovered	Normal	Normal	F	110
10	2	280	Yes	Recovered	Yes	Normal	F	Small
11	2	310	Yes	Died	Normal	Normal	F	Small
12	2	320	Yes	Recovered	Normal	Normal	F	140
13	2	320	Yes	Died	Normal	Normal	M	Small
14	2	340	Yes	Died	Normal	Normal	M	Small
15	2	350	No	Recovered	Normal	Normal	M	Small
16	2	370	Yes	Recovered	Normal	Normal	F	110
17	2	370	Yes	Recovered	Normal	Normal	F	120
18	2	380	Yes	Died	Normal	Normal	M	Small
19	2	390	Yes	Recovered	Normal	Normal	F	Small
20	2	400	Yes	Recovered	Normal	Normal	M	Small
21	2	410	Yes	Died	No specimen		M	Small
22	2	420	Yes	Died	Normal	Normal	M	Small
23	2	420	Yes	Died	Normal	Normal	M	Small
24	3	300	Yes	Died	Normal	Normal	F	Small
25	3	330	Yes	Died	Normal	Normal	..	Small
26	3	340	Yes	Died	Normal	Normal	F	Small
27	3	360	Yes	Died	Normal	Normal	F	Small
28	3	360	Yes	Paralyzed	Normal	Normal	F	Small
29	3	380	Yes	Died	Normal	Normal	F	Small
30	3	400	Yes	Died	Normal	Normal	M	120
31	3	410	Yes	Recovered	Normal	Normal	F	160
32	3	430	Yes	Died	Normal	Normal	F	230
33	3	500	Yes	Recovered	Normal	Normal	M	130
34	4	440	Yes	Died	Normal	Normal	F	260
35	4	550	Yes	Recovered	Normal	Normal	F	280
36	4	610	Yes	Died	Normal	Normal	M	390
37	4	640	Yes	Paralyzed	Normal	Normal	M	280

There was some burning at the electrodes caused by the current density, but there was no indication of any actual burning of the cerebral cortex.

A study of Table VII shows that 51 per cent of the rats died or were paralyzed as the result of contact with the 500-volt continuous current circuit, but the cause of death can not be ascribed to gross damage to the nervous system. It is hoped that the sections which are being prepared may give some information concerning the cause of death.

1000-Volt D-C. Series. Thirty-three rats were tested at this voltage; the duration of the shock varied from instantaneous contact to four seconds. No rats,

irrespective of size, survived a contact of one second or longer with this circuit. Of the thirty-three shocked nine, 27 per cent, recovered; twenty, 61 per cent, died; and four, 12 per cent, were paralyzed. In this series the central nervous system of the paralyzed rats was found to be grossly normal at autopsy. The average resistance was 1365 ohms.

These rats showed the clonic movements of the legs which appear to be so characteristic of continuous current shocks. The contraction of the muscles was somewhat greater than with the 500 volts continuous current, but not nearly as great as with the alternating currents.

Breathing was shallow and irregular and those rats study. This series is characterized by a high percentage of fatalities and the most prominent feature noted was persistent priarpism (permanent erection) in the males.

Comparison of the Alternating and Continuous Series

Exact comparison between the results of shocks with alternating and continuous currents is impossible because the duration of the contact was not the same the size of the animals differed with corresponding differences in current, and the number of animals varied in the two series. There is also the factor of the relative strength and health of the rats at the time of experimentation, which it is impossible to ascertain.

TABLE VIII
1000-VOLT D-C. SERIES

Rat No.	Duration of shock—sec.	Current milliamperes	Artificial respiration	Result	Gross hemorrhage		Sex	Wt. gr.
					Brain	Cord		
1	Inst.	..	Yes	Recovered	Normal	Normal	F	Small
2	Inst.	..	Yes	Paralyzed	Normal	Normal	M	Small
3	Inst.	..	Yes	Died	Normal	Normal	M	Small
4	Inst.	..	Yes	Died	Normal	Normal	M	Small
5	Inst.	..	Yes	Recovered	Normal	Normal	M	Small
6	Inst.	..	Yes	Died	Normal	Normal	M	Small
7	Inst.	..	Yes	Recovered	Normal	Normal	F	Small
8	Inst.	..	No	Recovered	Normal	Normal	..	Small
9	Inst.	..	Yes	Recovered	Normal	Normal	..	Small
10	0.5	..	Yes	Paralzyed	Normal	Normal	M	Small
11	0.5	..	Yes	Paralyzed	Normal	Normal	M	Small
12	0.5	..	Yes	Died	Normal	Normal	M	Small
13	0.5	..	Yes	Recovered	Normal	Normal	M	Small
14	0.5	..	Yes	Died	Normal	Normal	M	Small
15	0.5	..	Yes	Died	Normal	Normal	M	Small
16	0.5	..	Yes	Died	Normal	Normal	F	Small
17	0.5	..	Yes	Recovered	..	...	M	Small
18	0.5	..	Yes	Died	Normal	Normal	M	250
19	0.5	..	Yes	Recovered	Normal	Normal	F	230
20	0.5	..	Yes	Died	Normal	Normal	F	240
21	0.6	..	Yes	Paralyzed	Normal	Normal	M	Small
22	0.6	..	Yes	Recovered	Normal	Normal	F	200
23	1	600	Yes	Died	Normal	Normal	M	Small
24	1	640	Yes	Died	Normal	Normal	M	Small
25	1	710	Yes	Died	Normal	Normal	M	Small
26	1	730	Yes	Died	Normal	Normal	..	Small
27	1	740	Yes	Died	Normal	Normal	M	Small
28	1	750	Yes	Died	Normal	Normal	..	Small
29	1	..	Yes	Died	Normal	Normal	M	380
30	1	1000	Yes	Died	Normal	Normal	M	390
31	1	1100	Yes	Died	Normal	Normal	M	320
32	2	730	Yes	Died	Normal	Normal	M	Small
33	4	750	Yes	Died	Normal	Normal	M	Small

that recovered were very disturbed. Artificial respiration was used in every case but one. Although the heart beat strongly it was seldom possible to initiate breathing despite the greatest efforts. The chests of the animals were collapsed following the shock, and no air would enter the lungs. Four of the animals bled from the nose, eyes, or mouth, following the shock. The two paralyzed rats became incontinent after 24 hours although no blood was found in the urine.

No signs of gross injury to the nervous system could be detected in any of the rats that were used in this series and although there was considerable burning at the electrodes no damage to the surface of the brain was found. The cause of death may later be demonstrated by means of the sections being prepared for microscopic

On a-c. circuits there was a continuous severe tetanic contraction of the muscles which usually persisted for a few seconds after opening the circuit. The chest of the animal was greatly expanded, and the shock was usually followed by clonic movements of the legs. A large number of rats was subsequently found to be paralyzed in the hind legs and in these a hemorrhage was present in the spinal cord. Bleeding from the eyes or nose occurred in many of the animals.

On continuous current circuit the contraction of the muscles was not as severe as on the alternating circuit, and clonic movements were usually present while the current was flowing. Relatively few of the animals were paralyzed and only one of these showed the characteristic hemorrhage in the cord, so common in the

alternating series. Few gross injuries could be detected in the central nervous system. Bleeding from the nose was only observed at the higher voltages.

After contact with the a-c. circuits the hair of the rats was ruffled and stood out from the body. The fur on the rats shocked on continuous current circuits, on the other hand, lay smooth and unruffled. When rupture of the blood vessels in the eye occurred the pupil was in every case found to be greatly constricted.

110-Volt Alternating and Continuous Series. After contact with the alternating current at 110 volts, 64 per cent of the rats recovered and 36 per cent died or were permanently injured, in contrast to 85 per cent that recovered and 14 per cent dead or injured after contact with the continuous voltage circuit. The duration of the shock was greater on the continuous than on the alternating circuit. From this it must be concluded that alternating circuits of 110 volts are more dangerous to rats than continuous circuits of the same voltage.

220-Volt Alternating and Direct Series. Here again the shocks were longer with the continuous than with the alternating potentials, provided rat No. 29, which received a 35-second shock (Table II) is eliminated. Seventy-two per cent of the animals died or were injured with the a-c. circuit as compared to 47 per cent with the continuous circuit. The conclusion is that the continuous 220-volt circuit is less dangerous than the 220-volt alternating circuit; however, the difference is not as great as in the 110-volt series.

500-Volt Alternating and Continuous Series. In these two series the duration of the shock was the same. Of the alternating series 38 per cent recovered, 12 per cent died, and 50 per cent were paralyzed. In the alternating series a large number was paralyzed and few died, while in the continuous current series the reverse is the case. If dead and paralyzed rats are grouped together, the total for the alternating group is 62 per cent in contrast with 51 per cent for the continuous potential group. Both circuits may be considered as being equally dangerous to rats.

1000-Volt Alternating and Continuous Series. No rats survived a continuous potential of 1000 volts for more than one second while with the circuits of the same alternating voltage several rats were resuscitated after a shock lasting three seconds. The percentage of dead and permanently injured at this voltage was 73 per cent in the continuous group and 71 per cent in the alternating. A 1000-volt continuous current circuit is therefore much more dangerous to rats than an alternating circuit of the same voltage.

This series was characterized by ejaculation of the males on the alternating circuit and persistent priarpism on the continuous circuit. In these series there were also severe injuries at the site of the electrodes.

Artificial Respiration. Several methods of artificial respiration were tried, as it was difficult to find an ideal procedure. It was not possible to insert a tracheal tube to fill the rats' lungs with air; with a larger animal such a procedure would be ideal.

One of the methods tried consisted of a respiration bottle in which it was possible to alternately raise or lower the pressure by means of a pump. The rat's body was placed inside of the bottle with the head outside. A rubber diaphram fitted snugly about the neck. This method was not satisfactory and was abandoned.

The most successful method for rats was to place the animal on its back and alternately compress and release its chest, at the same time holding the tongue out of the mouth. In some cases it was found advantageous to stroke the throat to remove any mucus that obstructed the passage of air.

Adequate artificial respiration is of prime importance. Urquhart[4] believed that with proper artificial respiration all of the animals could be saved in which the current passed through the head only, provided no actual burning of the nervous system or brain occurred. On this basis he proposed his theory of a temporary block in the respiratory center without permanent damage.

In the present experiments the brain was actually burned in only a few cases and all of the rats' hearts beat strongly following the shock. If Urquhart's theory is correct it should have been possible to resuscitate nearly every rat provided the artificial respiration was adequate. As shown by the results, many rats were subsequently found to have large hemorrhages in various parts of the central nervous system, particularly in the spinal cord. At least five rats died within less than four hours after the shock as the result of hemorrhages in the fourth ventricle of the brain pressing on the respiratory center. In the present experiments a large number of rats never breathed after the injury and died at once. At autopsy developing hemorrhages in the central nervous system were found in many. It is the opinion of the authors that few if any of these rats could have been saved by any means of artificial respiration. Sections of the central nervous system of all these rats are being prepared and it is hoped that in these cases the cause of death may be demonstrated.

In general, artificial respiration was more successful with rats shocked by the high voltage a-c. circuits than with those shocked by the corresponding continuous current circuits. In the case of the rats shocked by alternating current the chest was expanded and by manipulation air could be drawn into the lungs and breathing initiated. On the continuous current circuits, on the other hand, the chest was usually completely collapsed following the shock and no air could be forced into the lungs.

In the rats that recovered, some breathed fast and shallowly, and in others the breathing was slow and labored. In many cases it was irregular and a series of five or ten quick breaths would be followed by a slight pause. Often these respiratory difficulties continued for several days until the rats were killed. These abnormalities indicate injury to the respiratory system.

None of the rats died due to primary cardiac injury; deaths were invariably due to respiratory failure.

It is important that artificial respiration be started immediately following the shock, as the slightest delay increases the probability of death.

Activity of the Rats Following the Shock

Few of the rats were active immediately following a shock at any voltage. When breathing began they usually lay quietly from five to ten minutes to half an hour. When they attempted to walk they were considered as recovered. Rats that later appeared normal were quiet for the first twenty-four hours and refused food and water. The paralyzed rats never became active, never ate, and could only be kept alive three or four days.

Resistance

The resistance of the animals was found to decrease with the increase in the weight of the rats. This is

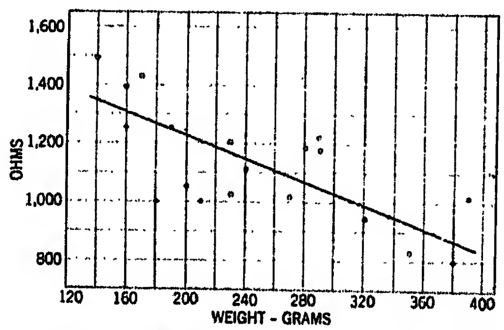

Fig. 1—Variation of Resistance with Size of Animals for the 1000-Volt A-C. Series

clearly indicated by the curve in Fig. 1, where the resistance in ohms is plotted against the weight in grams for the twenty-eight rats tested at an alternating potential of 1000 volts. Similar curves were found for the other series.

These experiments give the average values of the resistance of the rats as follows:

	Resistance ohms	
Voltage	A. C.	D. C.
110	3090	2685
220	1890	1635
500	1425	1385
1000	1140	1365

There is a large variation in resistance between the different series and part of this at least is caused by variation in the weight of the animal. For example, the rats tested with a 1000-volt alternating current were large compared to the majority of the rats tested with the same continuous potential.

As stated before the total resistance offered by an animal to the flow of current is made up of two parts, one the contact resistance and the other the ohmic resistance of the body. It is clear from a study of the resistance results in the case of rats that the contact resistance drop is of the form of a voltage drop which is practically independent of the current. The authors have calculated the value of this contact resistance voltage drop on the basis that the current through the animal equals the applied voltage minus the contact voltage divided by the resistance. On the basis of an average ohmic resistance of about 1200 ohms per animal the contact voltage drop equals 70 volts.

The current increased on long time applications and in some cases where the time was very long it nearly doubled in value. In most cases, however, the increase amounted to about 10 per cent.

Current

The current that passes through the animal is of great importance in determining the injury that will result from the shock, but it is not the only factor. Other clearly evident factors are the voltage of the circuit and the duration of the shock.

In these tests no correlation was found between the current under a given set of conditions and the resulting injury. As already pointed out, the current that flows depends to a considerable extent upon the size of the animal.

The ideal condition would be to know not only the actual amount of current that passed through the organ to be studied when the electrodes are applied to the body, but also the current density in that organ.

Voltage

Many data have been presented concerning the effect of the voltage and it is clear that the injuries increase as the potential is raised. It is very interesting to note again the fact that the initial shock is of importance. The 500- and 1000-volt a-c. tests, where the voltage was not maintained but fell rapidly to approximately 100 and 220 volts respectively, produced injuries much greater than the alternating 110- and 220-volt circuit experiments. In fact the injuries compare very well with those produced on the respective constant high-voltage circuits. It is therefore clear that the initial shock is of great importance in determining the injury to the animal. In this regard it would be interesting to know if there would be any difference in the injury produced by closing the a-c. circuit at different points of the voltage wave.

Hemorrhages

Hemorrhages were observed following the shock in different portions of the body. In large numbers of the rats, particularly with those shocked on a-c. circuits, a small amount of blood emerged from the nose. This was thought to have been produced by a rupture of small blood vessels in the mucus membrane. Often blood was found in one or both eyes due to the rupture of vessels in the conjunctiva.

When artificial respiration was begun a rush of blood and frothy liquid came from the mouth of a number of rats. It was possible that hemorrhages had occurred in

the lungs of these animals. The methods of artificial respiration were, however, somewhat strenuous for such small animals.

The hemorrhages in the ventricles of the brain were caused by the rupture of the delicate blood vessels (choroid plexus) in the brain. Several of the rats died a few hours after apparent recovery, from large collections of blood in the cerebral ventricles.

The hemorrhages in the spinal cord were very typical for all cases and were caused by the rupture of a small artery in the posterior septum of the spinal cord at about the middle of the back (lower thoracic region). The blood escaped among the fiber tracts of the cord, and the hemorrhage often extended for a considerable distance up and down the cord. If the hemorrhage remained small and localized, little abnormality was produced in the behavior of the rats.

These hemorrhages were much more common as a result of shock with alternating than continuous currents. The time element seemed of little importance since they were as often found with short as with long exposure to the current. They were also common in the two series where the voltage was not maintained and the duration of the high-voltage shock was less than one hundredth of a second.

Urquhart[4] has shown that there is a rise of blood pressure to twice normal value immediately following a shock and he believes that this is responsible for hemorrhages. This theory would account for all the hemorrhages found in this investigation with the possible exception of those in the spinal cord.

Practically all of the spinal cord hemorrhages were caused by the rupture of small arteries in the spinal cord at the point of greatest curvature of the spine. The uniformity of the process is difficult to explain on the basis of a rise in blood pressure throughout the body. The duration of the shock had little to do with these hemorrhages. It may be that the sudden strong pull exerted by muscles when the a-c. circuit was closed, applied enough force upon the spine and subsequently upon the cord to mechanically break the artery at this point. The spinal cord, however, lies so free in the vertebral canal that it is difficult to imagine that any sudden pull on the spine, no matter how violent, could injure the blood vessels in the cord. The authors have advanced their theory as a possible explanation of the spinal hemorrhages, but they have no proof that this is actually the case.

Paralysis

It was clearly demonstrated that the hind legs and the posterior portion of the body were paralyzed in a large number of rats after contact with the circuit. Paralysis was more common with those rats shocked with alternating than continuous currents.

Paralysis of the hind legs of rats shocked with continuous current, even though marked directly after the injury, had a tendency to decrease rapidly or even disappear entirely. Even in those rats in which the condition persisted and incontinence developed, no gross signs of hemorrhage were found in the spinal cord at autopsy. The paralysis observed after injury with continuous currents must be ascribed to other causes than hemorrhage. The characteristic injuries produced by continuous currents were convulsions, temporary paralysis, and priarpism. All these may be attributed to irritation of the central nervous system.

In the case of paralysis following shock with alternating circuits it was possible to gage in a rough way the extent of the hemorrhage. When the rats had recovered from the period of complete inactivity following the shock, and attempted to walk, they dragged their hind legs. If no active response to pinching the extremities was obtained during the first few hours following the shock it was concluded that the hemorrhage was severe, involving the lower portion of the spinal cord and completely interrupting the nerve tracts.

The subsequent behavior of this group of paralyzed rats was characteristic. After twenty-four hours, the great majority of the rats became incontinent and large quantities of blood were found in the urine. None of the animals could be induced to eat or drink, and they showed no activity. They would lie quietly in any position in which they were placed for hours at a time. None of them could be kept alive for more than three or four days.

At one time it was thought that the position of the electrodes on the tail might be responsible for the hemorrhages in the cord. As already stated, application of the electrodes to the head and one fore leg, or to one fore leg and the opposite hind leg produced the same effect. It must therefore be concluded that the paralysis of the hind legs was due to hemorrhage in the rats shocked by alternating current. Although beginning hemorrhages in the cord were found in a number of rats that died as an immediate result of the shock, it is doubtful if the spinal cord injury was responsible for the death. The paralyzed rats had no hope of permanent recovery.

Summary

The following conclusions are drawn from this investigation.

1. The 110- and 220-volt a-c. circuits are more dangerous to rats than the corresponding continuous current circuits.

2. The 1000-volt continuous current circuit is more dangerous to rats than the a-c. circuit of the same voltage.

3. A large rat can withstand a greater shock than a small rat and still survive.

4. There is no difference between the sexes in their susceptibility to electric shock.

5. The longer the contact with a circuit the greater the chances of death.

6. The danger increases as the voltage is raised.

7. The contraction of the body musculature is greater on an alternating than on a continuous circuit.

8. The a-c. experiments are characterized in many cases by paralysis of the hind legs caused by large hemorrhages in the spinal cord.

9. Paralysis depends more upon the initial shock than upon the duration of the shock.

10. The death of the rats was due in every case to respiratory failure.

11. The three different positions of the electrodes investigated produced similar abnormalities.

12. A severe electric shock probably produces changes in the nervous system that are incompatible with life.

13. The death of rats that lived for only a few hours following the shock was found to be caused by hemorrhages produced in the brain by the current.

14. The injuries are not directly proportional to the amount of current that passes through its body. Not only must the initial voltage be taken into account, but also the duration of the contact and the size of the animal.

It must be kept in mind that these results can not be applied directly to man or to other animals.

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